

Faculty of Engineering

Strength Optimization of Stabilized Peat Using Scrap Tire with Additives

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Strength Optimization of Stabilized Peat Using Scrap Tire with Additives

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A thesis submitted

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



Signature

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ABSTRACT

Peat soils are problematic for construction due to high moisture and organic content, low shear strength, and high compressibility. This study examines optimization of stabilized peat strength using Ordinary Portland Cement (OPC), recycled tire materials (rubber crumb (RC) and rubber powder (RP)); and a calcium-based biomass resin stabilizer (SH-85) to identify an optimum additive combination that improves subgrade performance and promotes waste reuse. Peat from Kg. Endap, Kota Samarahan, Sarawak was characterized for physical, index, and mechanical properties; tests comprised Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) at 7, 28, and 56 days, supported by Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) for microstructural analysis. Mix designs varied RC/RP at 5%, 10%, and 15% and SH-85 at 3%, 6%, 9%, and 12%, and cement fixed at 5% by dry weight. The optimum formulation of peat + 5% OPC + 15% RC + 6% SH-85 achieved UCS above 345 kPa and CBR exceeding 12%, meeting requirements for subgrades. SEM/EDX indicated a denser, cemented matrix with fewer voids and higher calcium and silicon, consistent with cementitious gel formation and improved bonding. Numerical modelling in GeoStudio (SIGMA/W, SLOPE/W) assessed embankment loading at field scale; a 300 mm stabilized layer reduced settlement to the CREAM threshold of 200 mm and increased the factor of safety to acceptable standards. The Modified Cam Clay model represented compressibility better than Mohr-Coulomb. The findings confirm that combining scrap-tire materials, cement, and SH-85 improves peat strength, stiffness, and stability, supporting resilient infrastructure on problematic soils and linking microstructural enhancements with mechanical performance.

Keywords: Peat stabilization, scrap tire rubber, SH-85, cement, UCS, CBR, SEM, EDX, GeoStudio, sustainable geotechnics.

Pengoptimuman Kekuatan Tanah Gambut Distabilkan Menggunakan Tayar Terpakai Berserta Bahan Tambahan

ABSTRAK

Tanah gambut bermasalah untuk pembinaan kerana lembapan dan bahan organik tinggi, kekuatan ricih rendah dan kemampatan tinggi. Kajian ini meneliti pengoptimuman kekuatan gambut distabil menggunakan Simen Portland Biasa (OPC), bahan kitar semula tayar terpakai iaitu serpihan getah (RC) dan serbuk getah (RP) serta penstabil resin biojisim berasaskan kalsium (SH-85). Tujuan kajian adalah membangunkan gabungan bahan tambah optimum untuk meningkatkan prestasi kejuruteraan gambut bagi aplikasi subgred sambil menggalakkan guna semula sisa lestari. Gambut dari Kg. Endap, Kota Samarahan, Sarawak dicirikan bagi sifat fizikal, indeks dan mekanikal. Ujian makmal adalah meliputi UCS dan CBR pada 7, 28 dan 56 hari pengawetan dan disokong oleh SEM-EDX untuk analisis mikrostruktur. Reka bentuk campuran menggunakan RC atau RP pada 5%, 10% dan 15% serta SH-85 pada 3%, 6%, 9% dan 12%, dengan kadar tetap simen iaitu 5% daripada berat kering. Campuran optimum gambut + 5% OPC + 15% RC + 6% SH-85 mencapai UCS >345 kPa dan CBR >12% yang memenuhi keperluan kejuruteraan bahan subgred. Imej SEM menunjukkan matriks lebih padat dan tersimen dengan pengurangan rongga, manakala EDX mengesahkan peningkatan kalsium dan silikon, menandakan pembentukan gel bersimen serta ikatan yang lebih baik. Pemodelan berangka dengan GeoStudio (SIGMA/W, SLOPE/W) menilai prestasi di lapangan bagi beban tambakan secara menyeluruh. Penstabilan lapisan setebal 300 mm dapat mengurangkan mendapan tanah kepada had yang ditetapkan CREAM iaitu 200 mm dan menaikkan faktor keselamatan ke tahap yang diterima industri. Model Modified Cam Clay menunjukkan kebolehmampatan gambut yang lebih baik daripada Mohr-Coulomb.

Dapatan mengesahkan gabungan bahan tayar, simen dan SH-85 dapat meningkatkan kekuatan, kekakuan dan kestabilan gambut secara ketara, serta menyokong pembangunan infrastruktur bagi tanah bermasalah dan membuktikan penambahbaikan mikrostruktur dan prestasi mekanikal

.***Kata kunci:*** *Penstabilan gambut, getah tayar skrap, SH-85, simen, UCS, CBR, SEM, EDX, GeoStudio, geoteknik mampan.*

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LIST OF ABBREVIATIONS

UCS	Unconfined Compression Strength
CBR	California Bearing Ratio
OPC	Ordinary Portland Cement
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
LOI	Loss of Ignition
SEM	Scanning Electron Microscope
BS	British Standard
MS	Malaysian Standard
ASTM	American Standard of Testing Material
USDA	United States Department of Agriculture
XRD	X-ray diffractometry
EDX	Energy-Dispersive X-Ray Spectrometry
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
MCC	Modified Cam-clay
RC	Rubber Crumb
RP	Rubber Powder
Pt	Peat
C	Cement
SH-85	Soil Hardener 85

LIST OF SYMBOLS

G_s	Specific gravity
w	Moisture content
F_c	Fiber content
A_c	Ash content
O_c	Organic content
g	Gram
µm	Micrometer
mL	Mililiter
mm	Milimeter
m	Meter
°C	Degree celsius
%	Percentage
M	Mass
ρ_d	Dry density of soil
ρ_w	Specific gravity of the soil
nm	Nanometer
kV	Kilovolt
C	Carbon
O	Oxygen
N	Nitrogen
S	Sulfur
Ca	Calcium
Fe	Iron

LIST OF SYMBOLS

Si	Silicon
Al	Aluminum
La	Lanthanum
e	Initial void ratio
γ_{sat}	Saturated unit weight
γ_d	Dry unit weight
λ	Compression index
κ	Swelling index
ν	Poisson's ratio
E_s	Elastic modulus
K_x	Hydraulic conductivity
φ'	Effective friction angle
OCR	Over consolidation ratio
kPa	Kilopascal
kN	Kilonewton
Cu	Undrained shear strength

CHAPTER 1

INTRODUCTION

1.1 Background

Geotechnical engineers around the world continue to face major challenges when constructing infrastructure on soft soils such as clay and peat. This issue remains both typical and critical, as these weak and compressible soils are widespread globally. Many engineers have attempted to avoid such problematic ground conditions due to the numerous difficulties involved, including limited site accessibility and the inherent geotechnical limitations of soft soils, particularly their low strength, poor durability, and insufficient stiffness. In particular, the problematic nature of peat soil in subgrade construction underscores the importance of addressing pavement stability and long-term performance, especially in regions where infrastructure development over peatlands is unavoidable.

The term of soft soil is referred to any soil that is vulnerable to collapse or induces undue settlement when the superstructure is constructed over it (Mathew & Sasikumar, 2017; Mohamad et al., 2016). According to Al-Bared et al. (2018), soft soil refers to a low shear strength soils having soil properties that often do not fulfil design requirements and show excessive settlement when loaded. Peat is categorized by its high-water content, compressibility and low shear strength (Ayeldeen & Kitazume, 2017; Mahmood et al., 2019; Ibrahim et al., 2020). Research conducted by Khing (2016) and Rahgozar & Saberian (2016) pose major geotechnical challenges in peat stabilization. Owing to these poor physical characteristics, various researchers agreed that peat soils are not suitable for the foundation of any engineering structure (Mohamad et al., 2016; Al-Bared et al., 2018;

Mohd Daud & Nik Daud, 2019; Md Zahri & Zainorabidin, 2019a) due to the soil's behaviour that also leads to significant failures, such as foundation instability and excessive settlement. As a result of the issues, it is obvious that peat soil requires significant improvement prior to construction.

1.2 Peat in Malaysia

Peat soils form a notable part of Malaysia's natural terrain and are distinguished by their high levels of organic matter, low shear strength, and significant compressibility. These soils are primarily concentrated in coastal zones across Peninsular Malaysia, Sarawak, and Sabah, collectively accounting for roughly 8% of the nation's total land area with an estimated 2,457,730 hectares out of 32,975,800 hectares (Huat, 2006; Kolay & Pui, 2010; Kolay, Aminur, et al., 2011; Moayedi & Nazir, 2018). Prominent peatland zones include the Johor and Sarawak basins, in addition to expansive swamp regions in Selangor and Pahang. Typically, these deposits are found in low-lying flood-prone areas or adjacent to major river systems. Due to their weak mechanical properties, natural peat is generally unsuitable for direct construction use, presenting considerable engineering challenges particularly with regard to maintaining foundation integrity and minimizing excessive settlement (Bakhir et al., 2024; N. Wahab et al., 2019).

Peat formation in Malaysia is influenced by factors such as climatic conditions, hydrology, and vegetation types (Kazemian et al., 2011a). The tropical climate, with abundant rainfall and high humidity, promotes the accumulation of organic matter in waterlogged conditions. The dominant vegetation, including mangroves and swamp forests, contributes to the high organic content in peat. According to Aeries et al., (2023) the

accumulation of plant material, combined with slow decomposition rates due to the lack of oxygen in waterlogged soils, leads to the gradual buildup of peat over thousands of years.

The distribution of peatlands across Malaysia is closely tied to hydrological factors, particularly in areas with persistently high-water tables that promote soil saturation. These saturated, low-lying landscapes create ideal conditions for the formation of peat swamps. In Sarawak, for instance, nearly 70% of peatlands are located in regions exhibiting such hydrological characteristics (Aeries et al., (2023). One distinctive feature of these ecosystems is the formation of peat domes, which develop through the gradual accumulation of organic matter in waterlogged environments. These domes significantly enhance the carbon storage potential of peatlands (Dommain et al., 2015).

Microbial activity also plays a crucial role in influencing the rate of organic matter decomposition in peat soils. Variations in microbial communities are shaped by environmental conditions and nutrient levels, thereby affecting the long-term stability and composition of peat. In addition to hydrology and climate, anthropogenic influences have further altered peatland dynamics in Malaysia. Charters et al., (2019) highlighted that activities such as deforestation and agricultural land conversion have disrupted natural peat formation processes. These interventions often involve drainage and modification of hydrological patterns, which accelerate decomposition and elevate carbon release. Consequently, these changes undermine the capacity of peatlands to function as carbon sinks, while also contributing to broader environmental concerns, including increased greenhouse gas emissions and loss of ecological diversity.

Sarawak holds the largest share of peatlands in Malaysia, covering an estimated 1,697,847 hectares that approximately 69.08% of the nation’s total peat area and around

13% of the state's landmass (M. Sa'don et al., 2015; Construction Research Institute of Malaysia (CREAM), 2019). These peat deposits are predominantly situated along major riverine systems, such as the Samarahan-Sadong, Lupar-Saribas, Rajang, Baram, and Limbang. As shown in Figure 1.1, peat and organic soil are concentrated in the coastal regions of Sarawak. The map was retrieved from the Construction Research Institute of Malaysia (CREAM) report (2019) but is courtesy of the Minerals and Geoscience Department of Malaysia (JMG) and the Department of Agriculture (DOA).

Peat thickness in the region is highly variable. While some areas contain shallow layers only a few meters deep, others surpass depths of 10 meters. Findings by M. Sa'don et al., (2018) indicate that approximately 90% of Sarawak's peat qualifies as deep peat which defined as being over 1.5 meters thick, especially in low-elevation zones. The thickness tends to increase from coastal to inland areas. The peat found in Sarawak is marked by a high proportion of organic matter and humic substances; chemically complex, aromatic compounds known as humic substances that heavily influence its geotechnical behaviour (M. Sa'don et al., 2015). These components contribute to its extremely low shear strength and high compressibility, which pose considerable difficulties for construction and load-bearing applications. Based on its degree of decomposition and physical attributes, Sarawak's peat can be categorized into fibric, hemic, and sapric types, each with unique structural characteristics. Beyond engineering implications, these peatlands serve as major carbon reservoirs, playing a vital role in climate regulation and ecological balance.

From an infrastructure perspective, the widespread presence of weak, compressible peat presents serious limitations to development projects in Sarawak. Structural stability is often compromised, particularly in buildings and transportation networks. Additional

issues include challenges in retrieving undisturbed samples, difficulties in executing in-situ tests, and the technical complexity of peat soil stabilization. The ongoing research into the characteristics and stabilization of peat in Sarawak is essential for developing effective management strategies that balance ecological preservation with economic development. This requires the development of innovative strategies specifically designed to address its unique geotechnical challenges, thereby ensuring the long-term stability and performance of constructed facilities. Therefore, further research is required to create more reliable and cost-effective solutions for stabilizing peat.

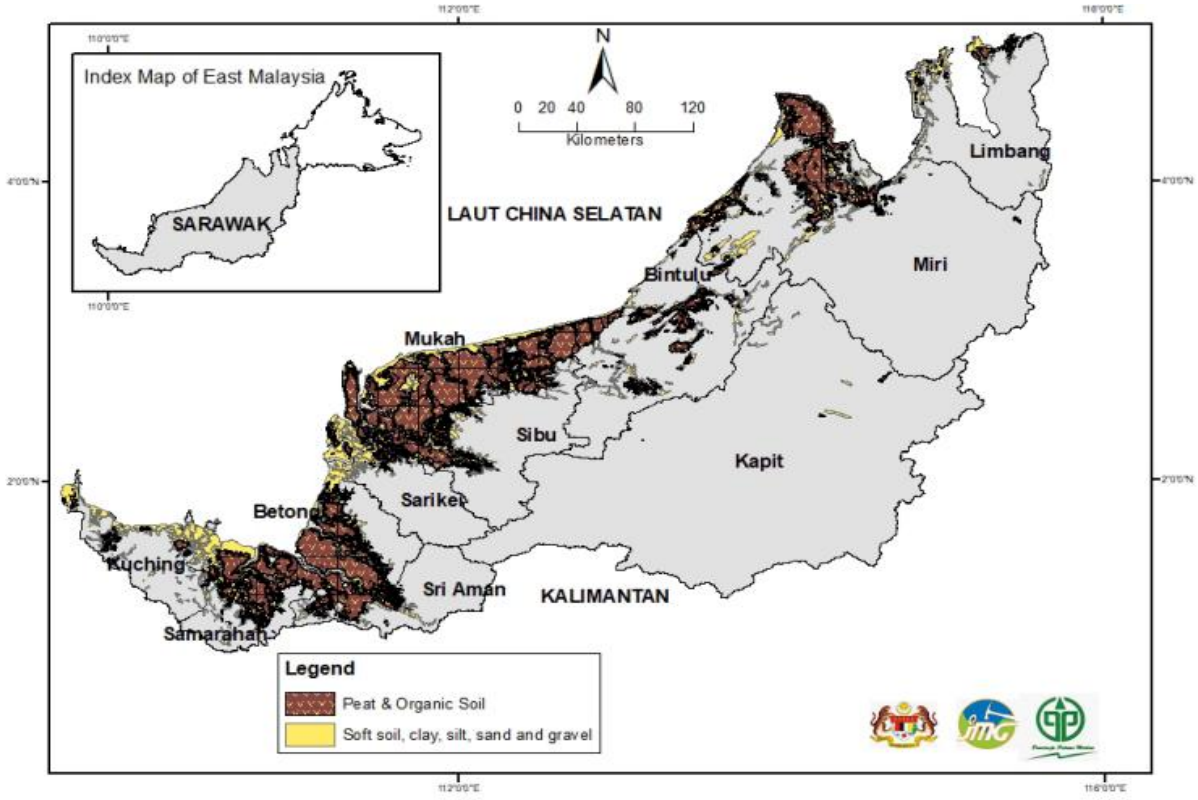


Figure 1.1: General Distribution of Peat & Organic Soils and Soft Soils in Sarawak
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1.3 Peat Treatment

The engineering behaviour of Malaysian peat is further complicated by its distinctive composition, which frequently comprises fibrous, hemic, and sapric varieties. Therefore, effective stabilisation techniques are required to improve its overall performance and load-bearing capacity. In Malaysia, peat is characterised by its higher organic content, lower bulk density, and high compressibility, which leads to instability when saturated. The material exhibits low strength, causing it inappropriate for direct load-bearing applications unless stabilised. The identified characteristics require the implementation of specialised engineering techniques for foundation support, including preloading, dynamic compaction, or chemical stabilisation.

The widespread occurrence of peat in Malaysia, especially in Sarawak, has led to increased investigation into various stabilisation techniques designed to address the inherent weaknesses of this soil type. Peat soil, known for its higher organic content, lower shear strength, and high compressibility, poses considerable challenges in the field of geotechnical engineering. Construction on peat soil frequently results in structural failures and expensive maintenance due to its inadequate bearing capacity and significant settlement tendencies. Consequently, there has been ongoing research of various stabilisation techniques aimed at improving the mechanical and physical properties of peat

soil. Among these, methods of reinforcement such as chemical stabilisation, fibre reinforcement, and geosynthetics have attracted significant interest. Methods including the use of cement, fly ash, and agricultural by-products such as sugarcane bagasse ash have demonstrated potential in enhancing the mechanical properties of peat (Bakhir et al., 2024; Kamaruidzaman et al., 2019; Kolay, Sii, et al., 2011). Furthermore, innovative techniques like electrokinetic stabilisation, as investigated by A. Wahab et al., (2021), have been examined, showing their potential to improve the shear strength and decrease the compressibility of peat soils. Nevertheless, in considering comprehensive examinations of peat stabilisation, there are still significant gaps that require additional investigation. A significant limitation in earlier studies is the insufficient comprehensive characterisation of both natural and reinforced peat.

Studies conducted by Al-Bared et al. (2018) and Fattah et al. (2015) have examined a range of techniques, encompassing chemical, mechanical, and biological approaches. Meanwhile, Mathew & Sasikumar (2017) emphasised further methods such as densification, reinforcement, and hydraulic modification. Nevertheless, these approaches entail significant financial expenditure. Among various options, one of the most promising approaches for construction on peat soil involves stabilising the peat soil using a suitable stabiliser. Soil stabilisation refers to the process of permanently modifying soil characteristics to enhance its strength and bearing capacity. The stabilisation may also reduce its sensitivity to water and the potential for volume changes. A variety of admixtures, including cement, lime, and fly ash, are available for the stabilisation of peat. Research has demonstrated that these techniques can alter the physical and engineering properties of peat, as evidenced by studies conducted by M. Sa'don et al. (2021), Moayedi & Nazir (2018) and Norazam et al. (2017). Numerous investigations indicate that soil

stabilisation methods contribute to improved strength and stability, especially in soft soils like peat and clay (Hauashdh et al., 2020; M. Sa'don et al., 2018, 2021; Mahmood et al., 2019; Nik Daud et al., 2019; Surjandari et al., 2019).

In Malaysian context, subgrade stabilisation involving peat has become increasingly important, especially in infrastructure projects such as roads, railways, and buildings. The primary concern with peat as a subgrade material is its tendency to undergo substantial volume change and decomposition when subjected to construction activities, which can result in excessive settlement and structural failure. This behaviour is primarily due to the high organic content of peat, which is highly moisture-sensitive and prone to softening when wet. Therefore, it is crucial to overcome these problems as to enhance the workability of peat for subgrade stabilization. While many researchers have focused on either the basic properties or the mechanical strength of peat, a holistic evaluation that integrates both aspects remains limited. This research aims to address this gap by characterizing the physical and mechanical properties of natural peat and reinforced peat through fundamental property determination, unconfined compression strength (UCS) tests, and California bearing ratio (CBR) tests. By doing so, this study will provide a more complete understanding of the effectiveness of reinforcement techniques in improving peat soil properties.

Regarding the long-term behavior of peat stabilization, significant knowledge gaps still exist specifically the strength enhancement, chemical interactions, and durability of the stabilized peat. Furthermore, additional experimental validation is needed to determine the optimum proportions and effectiveness of combining scrap tires with traditional or non-traditional stabilizers. Addressing these gaps will result in a more comprehensive

understanding of their feasibility and applicability in geotechnical engineering methods, as investigated in this study.

1.3.1 Peat Treatment using Scrap Tire

The instability of peat leads to significant construction failures, which requires comprehensive stabilisation techniques to enhance its mechanical properties. Conventional stabilisation methods, such as the application of cement and lime, have seen extensive use; nevertheless, these techniques frequently involve substantial cost and raise environmental issues, especially in relation to carbon emissions. As a result, studies into alternative, sustainable, and cost-effective stabilisation materials has increased significantly. Scrap tyre rubber is a material that has shown potential for use in soil reinforcement, attributed to its durability, elasticity, and sustainability properties.

The treatment of peat with scrap tyre materials is an innovative approach to tackling environmental issues such as waste management and soil stabilisation. Scrap tires, which are generally categorised as hazardous waste due to their durability and resistance to decomposition, have sparked interest in geotechnical and civil engineering fields. The shredded scrap tyre materials can be effectively repurposed to improve the structural qualities of peat, a soil type noted for its high compressibility and unpredictable nature. This dual-purpose technology addresses environmental concerns while also offering immediate benefits to building and civil engineering projects involving peat.

Despite numerous studies on peat stabilisation, significant deficiencies persist. Current research has predominantly concentrated on traditional stabilisers such as cement, lime, and fly ash, with less exploration of non-traditional and sustainable stabilisers such recycled tyre rubber. The mechanical and physical properties of peat reinforced with scrap

tyre material remain inadequately comprehended, especially for strength enhancement, long-term settlement behaviour, and microstructural interactions. Furthermore, although numerous studies have investigated the effects of rubber-based additions on soil characteristics, a thorough analysis that combines laboratory testing, microstructural assessment, and numerical modelling for peat reinforced with scrap tyre rubber is still completely unexamined.

This study aims to address these deficiencies by examining the viability of recycled tyre rubber as a stabilising agent for peat soil. The study will concentrate on characterising the physical and mechanical attributes of both natural and reinforced peat through basic properties determinations, unconfined compression strength (UCS) tests, and California bearing ratio (CBR) tests. The morphological properties of the reinforced peat will be examined by scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) spectroscopy to elucidate the microstructural alterations caused by scrap tyre reinforcing.

The use of crumb rubber from discarded tires in construction has gained attention not only for addressing geotechnical challenges but also for its environmental benefits (Yadav, 2023). Research has shown that incorporating recycled rubber particles into peat soils can significantly improve their unconfined compressive strength (UCS) (M. E. Mohamad et al., 2022). For instance, found that adding tire rubber to peat increases its shear strength while lowering the plasticity index, ultimately making the soil more suitable for supporting structures.

The elastic and durable nature of rubber particles contribute to better load distribution within the peat matrix, enhancing its overall performance under stress. Hilwane et al., (2021) emphasized that the inherent flexibility and resilience of crumb

rubber make it an effective additive for reinforcing soft soils. Studies also suggest that blending peat with various proportions of shredded scrap tires such as 5%, 10%, and 15% and combining them with cement-based stabilizers leads to notable improvements in both UCS and shear strength.

In particular, Hilwane et al., (2021) demonstrated that rubber-infused peat exhibits greater structural integrity, pointing to its value as a soil stabilization method. Similarly, M. Sa'don et al., (2021) reported enhanced strength and bearing capacity in both peat and clayey-silt soils when reinforced with shredded tire fibers. Beyond mechanical improvements, this approach offers a cost-effective and sustainable solution by repurposing waste materials for infrastructure development. Using scrap tires in this way serves a dual role: reinforcing weak soils and providing an environmentally responsible method of waste management.

The need to completely or partially replace traditional binders with more sustainable, durable and greener materials has been highlighted in recent soil stabilization techniques. These materials are expected to provide comparable or higher durability and strength performance than traditional binders in a similar curing period. Therefore, scrap tire waste in a form of rubber crumb and rubber powder could be used as a good alternative when combined with a minimum quantity of cement for subgrade stabilization. This by-product waste could be used as a filler and reinforcing material, with a traditional and non-traditional stabilizer to provide a durable and sustainable sub-grade layer. These materials have received a lot of interest in the construction field, and extensive research has been ongoing to determine the short and long-term performance of these additives.

In this study, scrap tires are introduced as a fiber-reinforcement material together with traditional and non-traditional stabilizer, as a suitable alternative to replace a huge consumption of traditional binders. The basic characteristic of the chemical stabilization process is the addition of stabilized materials to the peat, resulting in a chemical reaction. The chemical stabilizer will interact with peat and improves physical and engineering efficiency (Kolay, et al., 2011). Besides, these materials are chosen because it promotes the reutilization of industrial wastes, as well as its environmentally friendly characteristics and cost-effectiveness.

This study is important due to its impact on promoting sustainable practices within the field of geotechnical engineering. The use of scrap tyre rubber presents a practical method for enhancing peat stability while simultaneously contributing to sustainable waste management practices. This study promotes a transition towards more sustainable construction methods by minimising dependencies on cement and other stabilisers that contribute to high carbon emissions. The findings of this study will be beneficial for engineers, policymakers, and scholars looking for innovative and sustainable approaches to peat stabilisation, ultimately aiding in the creation of safer and more resilient infrastructure on problematic soils.

1.3.2 Peat Treatment using Traditional Stabilizer

Traditional stabilizers, including cement and lime, have been extensively utilized for peat improvement, providing increases in strength, reduced settlement, and enhanced durability. Traditional binders in soft soil stabilization significantly enhance the load-bearing capacity and durability of soft soils commonly encountered in geotechnical engineering. These binder's function through chemical processes that enhance the physical qualities of soil, transforming weak substrates into more stable and resilient materials

suited to construction applications, particularly in road and foundation projects. Cement serves as a binder, promoting pozzolanic processes that enhance soil stiffness, whereas lime modifies the chemical composition of peat, decreasing its plasticity and improving load-bearing capacity.

Traditional soil stabilizers such as cement and lime have long been recognized for their effectiveness in improving strength and reducing the compressibility of weak soils (Moayedi & Nazir, 2018). Among the most widely used additives are Portland cement, lime, and pozzolanic materials like fly ash, as noted by Debanath et al., (2021) and Anburuvel, (2024). These calcium-rich binders are commonly employed in geotechnical engineering due to their affordability, adaptability, and long-term durability, particularly in the treatment of soft and problematic soils (Khan et al., 2018). When introduced into the soil, these materials trigger chemical and physical changes that improve their structural behavior, leading to increased strength, stiffness, and better resistance to shrinkage.

Cement stabilisation is acknowledged for its effectiveness, as the hydration process yields compounds that contribute to substantial strength. In contrast, lime stabilisation enhances soil plasticity and moisture resistance by promoting chemical reactions with clay minerals found in the soil (Lindh & Lemenkova, 2023). Rodriguez-Navarro et al., (2023) stated in his study that lime undergoes a carbonation process that is crucial for its hardening, thus providing advantages to soils with high clay content. Additionally, research indicates that lime demonstrates greater efficacy when combined with other materials, resulting in improved performance compared to its use on its own as been studied by (Jangde & Khan, 2024).

Cement can be added to a range of soils and regarded as one of the practical and convenient methods of soil stabilization. However, the stabilization of the pavement base and sub-grade require a higher cement dosage and unfortunately, microcracking can occurs because of shrinkage produced by the heat of hydration in the cement. Other than that, although these traditional binders can improve a variety of soil engineering properties, they have several flaws, especially from the environmental point of view. For example, a huge consumption of cement creates a significant amount of carbon dioxide, which is a greenhouses gas, and hence is not an environmentally friendly material. It is important to find an alternative to cement stabilization that can minimise effects on the environment while maintaining the materials strength, stiffness, and long-term performance. The effectiveness of traditional stabilisers in treating peat soil is frequently constrained by humic acids, which can impede the pozzolanic reactions essential for achieving long-term stability. The higher organic content in peat may disrupt binding efficiency, resulting in reduced strength gain relative to stabilisation in inorganic soils. Excessive cement content can lead to brittle failure in stabilised peat, thereby reducing its long-term durability and flexibility under varying load conditions.

Furthermore, fly ash a byproduct of coal combustion, functions as a pozzolanic binder that reacts with hydroxide ions to produce cementing compounds, enhancing the strength of stabilised soil. Research demonstrates that the integration of fly ash with traditional binders such as cement or lime enhances engineering properties and promotes environmental sustainability through the utilisation of waste materials (Debanath et al., 2021; L. Liu et al., 2020). A recent study highlighted those combined binders, which integrate traditional materials with environmentally friendly additives, can enhance

performance and decrease the carbon footprint linked to standard cement production (Coudert et al., 2019; Jegandan et al., 2010).

Traditional additives also play a crucial role not only in enhancing strength but also in soil stabilization, which is required for reducing the swelling and shrinkage of expansive soils. This application significantly improves the structural integrity of embankments, pavements, and foundations (Wassie et al., 2023; Zada et al., 2023). The impact of these additives on soft soils varies significantly based on environmental conditions, additive type, and soil composition. Thus, current research aims to optimise additive formulations to improve their effectiveness.

Traditional binders, while beneficial, exhibit limitations, especially regarding their environmental impact and structural durability in adverse conditions. The production of Portland cement significantly contributes to greenhouse gas emissions, causing increased interest in alternative stabilisation methods that employ less environmentally harmful materials (Guo et al., 2025). This awareness promotes innovation in identifying sustainable alternatives to traditional binders, including alkali-activated materials or bio-based additives, which may decrease dependence on traditional approaches while preserving or improving stabilisation effectiveness. Therefore, a minimum amount of cement is utilised in this study to reduce dependency on traditional additives for peat stabilisation.

Although traditional methods for stabilizing peat have been extensively investigated, several critical limitations still require attention. A major concern is the long-term performance of cement-stabilized peat under acidic conditions, which are typical in organic soils. The presence of humic and fulvic acids can lead to the gradual leaching of stabilizing agents, ultimately weakening the treated soil structure over time (Cao et al.,

2023). This chemical degradation poses a significant threat to the sustainability of stabilization efforts. Furthermore, most current studies emphasize improvements in large-scale mechanical properties such as unconfined compressive strength while offering limited insight into the underlying microstructural changes that occur during stabilization. Understanding how stabilizing agents interact with organic particles at the microscopic level, including the formation of cementitious bonds and morphological transitions, is essential for refining treatment strategies and improving long-term durability (Ahmad et al., 2023). To bridge this knowledge gap, further investigation into the microstructural mechanisms of interaction between peat and various binders is necessary for advancing peat stabilization technology.

In recent years, concerns surrounding the economic viability and environmental impact of large-scale peat soil stabilization using conventional binders; particularly cement and lime have gained growing attention among geotechnical researchers. While these materials have demonstrated effectiveness in reducing compressibility and improving the strength of organic soils, their application at industrial scale often comes with significant trade-offs. Cement production, for example, is a well-known contributor to global CO_2 emissions, responsible for nearly 8% of total anthropogenic carbon dioxide output (Scrivener et al., 2018). Moreover, the cost of cement-based stabilizers can be prohibitive in regions requiring extensive ground improvement. This dual challenge, which is economic burden and environmental degradation, highlights the need for more sustainable stabilization practices.

Despite the extensive use of traditional binders, many studies have yet to fully explore the potential of combining them with alternative or waste-derived materials to

improve performance while lowering environmental costs. Recent investigations have started examining the effectiveness of hybrid stabilization approaches, including the use of industrial by-products, geopolymers, and recycled materials, which have shown promise in reducing dependency on cement (Daniel et al., 2025; Wibisono et al., 2019). However, such strategies remain underutilized in peat treatment contexts.

Addressing these gaps, the present study proposes a novel stabilization scheme that limits the use of cement by supplementing it with SH85, a commercially available, non-traditional stabilizer and rubber crumb sourced from recycled scrap tires. This combination aims to retain the mechanical benefits of cement stabilization while mitigating its environmental footprint and economic cost. Scrap tire rubber, due to its elastic properties and high durability, has shown potential to improve the load-bearing capacity and toughness of stabilized soils (Hilwane et al., 2021; M. Sa'don et al., 2021). Meanwhile, SH85 has been used effectively to improve soil strength and reduce water permeability, although its chemical composition remains proprietary.

To gain deeper insight into the stabilization mechanisms at play, this research will incorporate Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis. These techniques are essential for visualizing and characterizing microstructural changes in treated peat, such as particle bonding, matrix densification, and distribution of additives. By evaluating the interactions between peat particles, cement hydration products, and secondary additives at the microscopic level, the study seeks to advance the understanding of composite behaviour in stabilized peat systems, which remains a relatively underexplored area in current literature (Ahmad et al., 2023).

1.3.3 Peat Treatment using Non-Traditional Stabilizer

Conventional binders such as cement and lime have been widely applied in the stabilization of problematic soils due to their proven ability to improve strength and reduce compressibility. However, in the context of peat, which is characterized by extremely high moisture content, low shear strength, and high compressibility, the performance of these traditional materials can be limited and unsustainable in the long term (Krishnan & Govindaraj, 2024). The environmental implications of cement usage is particularly its high carbon footprint, and the economic cost associated with large-scale applications have prompted the exploration of alternative, more sustainable solutions.

In response to these concerns, researchers have turned their attention to non-traditional stabilizers, particularly those derived from agricultural or industrial waste. Additives such as Eco-Processed Pozzolan (EPP), rice husk ash, and sugarcane bagasse ash (SCBA) have gained traction for their environmental advantages and potential cost savings (Al-Bared et al., 2018; Ramdhiani & Rahayu, 2019). These waste-derived materials often enhance soil strength while reducing reliance on Ordinary Portland Cement (OPC), thus minimizing greenhouse gas emissions. Bakhir et al., (2024), for example, reported notable improvements in compressive strength of peat when stabilized with SCBA, without the need for high cement content. Similarly, studies have demonstrated that combining EPP with specific admixtures significantly improves the index and mechanical properties of organic soils while also mitigating shrinkage behaviour (Sulaiman et al., 2022; Sutarno & Mohamad, 2023).

Among the promising materials under investigation is SH85; a bio-derived stabilizer produced from agricultural biomass. Its formulation leverages industrial

byproducts rather than raw materials, aligning well with global sustainability goals and offering a low-carbon alternative to traditional cement (Vitales et al., 2022). Research indicates that SH85 not only contributes to improved strength and stability of treated peat soils but also enhances water retention and durability under variable environmental conditions. Moreover, SH85 has been shown to reduce dependency on cement while maintaining comparable engineering performance, offering both economic and environmental benefits as stated by Vitales et al., (2022).

Despite these advancements, several challenges remain. The performance of non-traditional stabilizers can be inconsistent due to variations in chemical composition, particle size, mixing ratios, and curing techniques. Dehghanbanadaki et al., (2013) and Sing et al., (2009) observed that insufficient binder dosages may result in inadequate strength development, undermining the effectiveness of stabilization efforts. Furthermore, most existing studies are laboratory-based and tend to focus on short-term performance metrics, leaving critical questions about long-term durability, behaviour under field conditions, and resistance to environmental challenges were unanswered (Rahmi et al., 2018).

To clarify the underlying mechanisms that govern the enhanced engineering performance of stabilized peat, this study incorporates both microstructural analyses and numerical simulations. These complementary approaches allow for both mechanistic understanding and predictive performance evaluation of treated peat as a subgrade material. Recent studies have begun to emphasize the importance of evaluating stabilization mechanisms at the microstructural level. Analytical tools such as Scanning Electron Microscopy (SEM) and Energy-Dispersive X-Ray Spectroscopy (EDX) provide valuable

insights into the formation of cementitious bonds and the distribution of stabilizing agents within the peat matrix (Hauashdh et al., 2020; Sulaiman et al., 2022). These microscopic evaluations are essential for understanding the interactions between organic matter and stabilizers and for optimizing treatment strategies. From a broader perspective, the significance of sustainable peat stabilization extends beyond engineering considerations. Peatlands function as critical carbon sinks, and irresponsible disturbance can lead to massive carbon emissions and biodiversity loss. Therefore, the use of green stabilizers such as SH85 not only contributes to infrastructure development but also supports environmental preservation and climate resilience.

High resolution techniques such as Scanning Electron Microscopy (SEM) combined with Energy Dispersive X-ray Spectroscopy (EDX) are indispensable for visualizing and quantifying the internal transformations induced by stabilization agents. In peat treated with waste rubber crumb, SEM and EDX revealed enhanced compactness of the peat matrix and identified elemental composition changes, underscoring the microstructural basis for observed strength increases as studied by Mohamad et al. (2022). Furthermore, studies using industrial byproducts such as silica waste in combination with cement have demonstrated dramatic UCS improvements that up to 744 kPa and SEM-EDX images confirmed the densification and humification trends in treated peat (Bujang et al., 2024). These microstructural observations not only validate the mechanical test results from UCS and CBR tests but also illuminate the formation of binding compounds such as ettringite and C-S-H gels with pore filling phenomena that contribute to strength enhancement and structural stability.

To assess the field scale behaviour of the stabilized subgrade, finite element analysis is employed using GeoStudio. Such modelling frameworks enable simulation of settlement behaviour under embankment loading, using constitutive soil models. In Central Kalimantan, Susila & Apoji (2012) demonstrated through PLAXIS simulations that Mohr Coulomb and hardening soil models can predict central embankment settlement realistically when calibrated with field data. Similarly, Yamazoe et al. (2023) shows the importance of accounting for time dependent characteristics in finite element analysis models for road embankments over peat, enhancing the reliability of long term settlement predictions. GeoStudio, encompassing modules such as SIGMA/W and SLOPE/W, supports coupled consolidation and staged loading simulations, allowing engineers to evaluate the deformation behaviour, pore pressure dissipation, and consolidation settlement of reinforced peat subgrades under realistic construction sequences. In this study, SEM and EDX imaging revealed how additives like cement, recycled rubber waste and SH 85 alter peat's internal structure. Visual evidence of pore filling, crystalline formation, and matrix densification can be assessed in relation to UCS and CBR outcomes.

Simultaneously, the used of GeoStudio modelling assess the performance of these enhanced materials under loading conditions, forecasting settlement behaviour in alignment with Malaysian design guidelines. Finite element analysis facilitates scenario testing, including variations in loading sequences and consolidation periods, to assess the stability and serviceability of peat subgrade treated with the optimum mix design. This analytical strategy links micro-scale mechanisms, such as the addition of cementitious structures and reduction of porosity, to macro-scale outcomes, including reduced settlement and enhanced load capacity. It offers a solid theoretical and practical foundation for the implementation of stabilized peat in low-volume road infrastructure.

Nonetheless, knowledge gaps remain in the current body of literature. There is a lack of comprehensive studies assessing the performance of SH85 and similar materials under diverse field conditions, including changes in moisture regimes and cyclic loading. Marto et al., (2016) and Vitales et al., (2022) highlighted the need for long-term monitoring and performance evaluation. Moreover, the synergistic effects of combining SH85 with other waste materials or cementitious binders have yet to be systematically explored. Addressing these gaps requires rigorous experimental programs supported by numerical modelling to identify optimal stabilizer combinations and dosages.

In conclusion, non-traditional stabilizers, particularly SH85, present a compelling pathway toward sustainable peat stabilization. While early research has shown promising results, further work is needed to assess their performance across variable environmental conditions, to understand long-term durability, and to enhance their microstructural integration with organic soils. Future research should focus on full-scale trials, performance modelling, and interdisciplinary approaches that balance engineering performance with ecological integrity.

1.4 Problem Statement

Construction on peat land in Malaysia has been rising in recent years as stated in several researchers in their studies (Hua et al., 2016; Ibrahim et al., 2020; Makinda et al., 2018; Wijeyesekera, Numbikannu, et al., 2016). Improving the engineering properties of peat is therefore crucial for better and more economic measures on infrastructure (Kolay et al., 2011; Mahmood et al., 2019). Unfortunately, in Sarawak, in-situ soils are often inadequate for project requirements, where, due to the availability of soft soil such as peat, some of the locations are insufficient for the loading requirements. To fulfil these

requirements, the affected soil must be treated to stabilize the soil in the designated area to provide a stable sub-grade and an adequate working platform for the construction works.

The stabilization of peat soils is essential in addressing the inherent challenges associated with their high compressibility, low shear strength, and significant moisture content, which can lead to substantial settlement and instability in engineering applications. Despite various traditional stabilizing methods, such as cement and lime stabilization, enduring concerns regarding environmental sustainability and cost-effectiveness remain prevalent (Wibisono et al., 2019). As peat comprises a high organic matter content, the introduction of traditional stabilizers often results in environmentally detrimental outcomes and may not be economically viable for wide-area coverage required in substantial peat regions (Pashaki, 2017). This study proposes that integrating alternative stabilizers, such as waste tire-derived materials in conjunction with various chemical additives, may offer a multidimensional solution to optimize the strength characteristics of stabilized peat.

This study aims to investigate the effectiveness and performance of waste tire materials with the addition of various percentage of non-traditional stabilizer (SH85) and minimum amount of cement for peat stabilization. While preliminary studies indicate that additives like waste tire-derived products can enhance the mechanical properties of soil substrates, their application specifically to peat remains underexplored (Hilwane et al., 2021; M. E. Mohamad et al., 2022). Recent advances highlight the potential of integrated approaches combining mechanical reinforcement and chemical stabilization to realize optimized strength characteristics. However, significant knowledge gaps persist regarding the optimum mix design, including the influence of varying waste tire percentages and

supplementary additives such as fly ash or sodium hydroxide on peat's performance as study conducted by (H. M. Mohamad et al., 2023; Rahgozar & Saberian, 2016).

The stability of the underlying soils needs a serious consideration to ensure that the engineering structures that has been construct can give long-term performance and enhance the durability. It is important to provide the optimum performance of the soil foundation because the loading of the infrastructure significantly affects the soil beneath it. Therefore, any soil foundations must provide a better engineering property such as shear strength, moisture resistance, stability and the durability by stabilizing it.

Construction problems for structures based on such soil-producing areas are urgently emerging. From a civil engineering perspective, peat and organic soils have been considered as a major category of problematic and challenging soils. In Sarawak, the investigation into potential improvements of soft or peat stabilization by various admixtures seems to be limited. Although many experimental studies on the geotechnical characteristics, chemical stabilization and reinforcement technique of peat reported in the literature, there are still a scarcity of information about the strength effect of processed tire-waste disposal using scrap tire as reinforcement materials for peat soil. Hence, the soil stabilization or reinforcement techniques with tire-waste disposal for construction may not only provide the alternative mean of recycling and reusing, but it also can help in making the best use of locally available materials. Indirectly, this will help to contribute to environmental concerns.

However, more research and analysis are needed to establish that these non-traditional stabilizers can be used as an alternate or primary soil stabilizing agent. It can also provide accurate data and information to other researchers. Thus, the focused of this

study is to demonstrate the feasibility of stabilizing fiber reinforced peat soil using scrap tire with the admixtures of traditional and non-traditional additives and to evaluate the peat's response to soil improvement specifically the strength optimization. The targeted strength to be achieved in this study is to exceed the threshold of 345 kPa from ASTM D4609-Standard Guide for Evaluating the Effectiveness of Admixtures for Soil Stabilization's criteria; and the targeted CBR value of 5% to 12% as been required in the Manual for the Structural Design of Flexible Pavement (2013) from JKR Specification. Several compressive parameters of the peat under study will be determined. The results are useful for identification of the compressibility characteristics and predicting the compression behaviour of sapric peat.

1.5 Aim and Objectives

This study aims to investigate the performance of reinforced peat soil stabilized with a combination of recycled rubber (crumb and powder) and chemical additives (Ordinary Portland Cement and SH-85), with particular focus on its application as a subgrade material in tropical peatland regions. The primary objectives are to develop a sustainable stabilization strategy that enhances the strength, durability, and deformation resistance of sapric peat, thereby mitigating common geotechnical challenges such as excessive settlement and low bearing capacity.

To achieve this aim, the research begins with a thorough characterization of both untreated and reinforced peat soil, focusing on their physical and mechanical properties. This foundational investigation, which includes basic index testing, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) testing, helps identify

how different reinforcement combinations influence the engineering behaviour of peat and guides the selection of an optimum stabilization mix.

Building on these mechanical insights, the study then explores the underlying mechanisms responsible for strength improvement through detailed microstructural and morphological analysis. Using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX), the formation of cementitious bonds, reduction in porosity, and elemental transformations are assessed to understand the chemical and physical interactions between peat and the stabilizing agents.

Finally, the optimum mix formulation is evaluated in a numerical modelling environment using GeoStudio (SIGMA/W and SLOPE/W) to simulate the real-world performance of a stabilized subgrade layer. The model analyses deformation, stress distribution, and slope stability under loading conditions, allowing for the validation of the stabilized system against design standards.

The interconnected objectives collectively enhance the understanding of reinforced peat soil behaviour, encompassing laboratory characterization, microscopic evaluation, and field-scale modelling. This approach effectively addresses every relevant issue and offers original insights into the domain of sustainable ground improvement.

1.6 Hypothesis

The integration of scrap tire material with both traditional and non-traditional stabilizers will significantly enhance the mechanical properties of peat, specifically unconfined compressive strength (UCS), California Bearing Ratio (CBR), and settlement resistance, thereby improving its suitability for use as a subgrade material in geotechnical engineering applications.

1.7 Research Questions

This study is guided by the following research questions:

What are the physical and mechanical characteristics of natural versus reinforced peat as determined by basic index properties, unconfined compressive strength (UCS), and California Bearing Ratio (CBR) tests, and how do different reinforcement strategies influence these properties?

How do the microstructural and morphological features of reinforced peat differ from those of natural peat when evaluated using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX)?

How does the optimum reinforced peat mixture perform in terms of settlement behaviour for subgrade applications, as assessed through numerical modelling using GeoStudio?

1.8 Significance of Study

This research offers valuable insights for highway authorities and the pavement industry by examining the potential use of scrap tire waste and calcium-based biomass-derived stabilizers as sustainable alternatives for peat soil stabilization, particularly in pavement construction. The study is especially relevant to Sarawak, where peat is prevalent and construction challenges are common. By incorporating minimal quantities of cement with supplementary additives; namely rubber crumb, rubber powder, and SH85 (a calcium-based powder sourced from biomass silica), this work aims to optimize subgrade stabilization techniques. The findings contribute to the advancement of chemical stabilization methods involving fiber-reinforced peat, highlighting the effects of various additive dosages on strength and settlement behaviour. In doing so, the study supports the

selection of appropriate stabilizer proportions tailored to the geotechnical properties of local peat. It also promotes the use of locally available waste materials to enhance soil strength, reduce dependence on imported construction inputs, and offer long-term stability for subgrade layers. Furthermore, by improving the load-bearing capacity of underlying soils, the research facilitates the creation of stable working platforms for subsequent pavement layers. This approach not only contributes to cost-effective infrastructure development on soft soils but also aligns with sustainability goals by reducing construction-related environmental impacts. Additionally, the study incorporates settlement performance analysis and risk assessment for stabilized peat embankments, offering practical guidance for future highway projects on problematic soils.

1.9 Scope of Study

This study adopts an integrated approach to evaluate the stabilization of peat soil through laboratory testing, microstructural analysis, and numerical modelling. Undisturbed peat samples are collected from Kota Samarahan, Sarawak. These samples were treated with shredded rubber crumb (5–15% by weight), ordinary Portland cement (fixed at 5%), and SH-85, a calcium-based biomass resin (3–6%).

The physical and mechanical properties of untreated and reinforced peat are assessed through standardized laboratory procedures, including organic content by the loss-on-ignition method, moisture content, specific gravity, and compaction behaviour by Standard Proctor test as per BS 1377: Part 2:1990. Strength performances were evaluated using unconfined compressive strength (UCS) tests on cylindrical specimens (38 mm × 76 mm), cured at intervals of 7, 28, and 56 days, with a minimum target UCS of 345 kPa based on ASTM D4609. California Bearing Ratio (CBR) tests were examining load-

bearing capacity on compacted samples (152 mm × 178 mm) cured for 7 and 28 days. The results were benchmarked against the subgrade performance criteria recommended by the Public Works Department (PWD) of Malaysia (5–12% CBR).

The research design was developed based on the objective of evaluating the improvement in peat soil properties when stabilized with a combination of traditional (cement) and non-traditional (rubber crumb, rubber powder, and SH-85 biomass silica) stabilizers. The design was inspired by previous studies on peat stabilization (M. Sa'don et al., 2021; Moayedi & Nazir, 2018) and adapted to the local peat conditions in Sarawak. Laboratory trials and literature review were used to determine suitable additive ranges that balance strength improvement, workability, and cost-effectiveness.

For sample preparation, the collected peat was first air-dried, manually broken down to eliminate large fibrous clumps, and sieved through a 5 mm sieve to ensure uniformity. The peat's initial moisture content was determined, and the required dry weight for each batch was calculated. Cement was fixed at 5% (by dry weight of peat) as a constant binding agent. Rubber crumb and rubber powder were each tested at 5%, 10%, and 15%, while SH-85 biomass silica powder was incorporated by dry weight at 3%, 6%, 9%, and 12%.

The mixing process involved thoroughly blending the dry additives (cement, rubber crumb or powder, and SH-85) with the dried peat until homogeneity was achieved. Water was then added gradually to reach the target moisture content, determined from Standard Proctor compaction tests. The mixture was compacted in layers using the Standard Proctor procedure to achieve the maximum dry density (MDD) for each design mix. All prepared

samples were then cured under controlled moisture and temperature conditions before mechanical and microstructural testing.

Microstructural analyses were conducted using Scanning Electron Microscopy (SEM) to identify changes in pore structure, matrix densification, and bonding between peat fibers and additives such as cementitious compounds, rubber particles, and SH-85. Elemental composition will be determined via Energy Dispersive X-ray Spectroscopy (EDX), focusing on key constituents including carbon, oxygen, calcium, and silica. This phase aims to correlate microstructural transformations such as calcium silicate hydrate (C-S-H) formation with observed improvements in strength and durability.

The performance of the optimum mix was then be assessed through numerical modelling using GeoStudio (2022) finite element software, specifically the SIGMA/W module for analysing deformation and consolidation behaviour, and the SLOPE/W module for evaluating slope stability. The stabilized peat layer was simulated under embankment loading, with input parameters derived from laboratory results and peer-reviewed literatures. The model was analysed to examine settlement behaviour across different curing periods and construction stages. SIGMA/W was used to predict vertical settlement and lateral displacement of both untreated and stabilized peat layers, while SLOPE/W was applied to calculate the factor of safety (FoS) against potential slope failure. This combined finite element analysis provides a more comprehensive understanding of the subgrade performance, ensuring that both deformation control and stability criteria are met for low-volume road applications on tropical peat. The findings are expected to inform practical stabilization strategies while enhancing the understanding of additive with peat interaction mechanisms critical to soft soil engineering.

Limitations of this research include the scale of testing (laboratory-based results may differ from field-scale performance), the fixed percentage of cement which may not represent the absolute optimum, and the limited curing period adopted for practical purposes, which may not capture very long-term behaviour. Additionally, the variability of natural peat properties between locations means the findings are most applicable to peat soils with similar characteristics to those tested in this study.

1.10 Thesis Organization

This thesis is structured into six chapters, each addressing a key component of the research process, from problem identification to conclusions and recommendations:

i. Chapter 1 – Introduction

   Provides the background of the study, problem statement, research objectives, scope, and significance. It also outlines the limitations of the study and the overall structure of the thesis.

ii. Chapter 2 – Literature Review

   Critically reviews previous research on peat soil properties, stabilization methods, and the use of waste-derived materials such as scrap tire rubber and SH-85. It also highlights relevant engineering performance criteria, microstructural analysis techniques, and research gaps that form the basis for this study.

iii. Chapter 3 – Research Methodology

   Describes the procedures adopted for sample collection, laboratory testing, and microstructural characterization, as well as the design of the numerical

modelling framework. It details the materials used, mix designs, test standards, and analytical tools applied.

iv. Chapter 4 – Results and Discussion

Presents and interprets the experimental results, including physical properties, UCS and CBR performance, failure modes, and microstructural changes. Findings are compared with standards and literature to identify the optimum mix design.

v. Chapter 5 – Numerical Modelling

Reports the outcomes of settlement and stability analyses using GeoStudio's SIGMA/W and SLOPE/W modules. It compares untreated and treated peat performance under embankment loading, evaluates the effect of stabilization layer thickness, and validates the laboratory findings at a simulated field scale.

vi. Chapter 6 – Conclusions and Recommendations

Summarizes the key findings, addresses the research objectives, and provides recommendations for practical implementation and future research directions.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter critically reviews the classification and engineering behaviour of peat soils. Al-Bared et al., (2018) and O'Kelly & Pichan, (2013) identify that soft soils, such as peat and other organic materials, pose unique challenges in the field of geotechnical engineering. In this chapter, the unique properties of organic soils, including their high permeability, porous texture, and dark coloration, are analysed in accordance with the definition of organic soils by ASTM (2007). The investigation presents a critical analysis of various studies, focusing on the mechanical performance of untreated and reinforced peat. It explores the potential of emerging materials, such as shredded scrap tires, as effective additives for improving soil properties (Hilwane et al., 2021; M. Sa'don et al., 2021). Key issues discussed include the influence of peat's high compressibility and low strength on construction, the potential of sustainable stabilisation methods, and the importance of optimizing additive proportions for strength and durability. However, in peat stabilisation studies, thorough mix-design frameworks, particularly those involving fly ash, NaOH, or hybrid blends remain largely unexplored. This chapter aims to synthesize existing knowledge and highlight notable gaps in research, especially regarding long-term performance assessments and the impact of different compositions on the strength optimization of peat using innovative waste materials.

2.2 Peat Soil Classifications and Characteristics

From the agricultural field perspective, based on USDA (Soil Taxonomy) soil that have more than 20% of the organic content was classified as peat. This is contrary to the soil science perspective, which described more than 35% of the organic content as peat. However, from the geotechnical engineering field by ASTM Standard, peat can be identified as the soils that have an organic content more than 75% while soil with organic content below than 75% is known as an organic soil. This forms a fundamental distinction between the views of a geotechnical engineer and those of a soil scientist (Zainorabidin & Wijeyesekera, 2007b).

Peat soils in Malaysia, particularly in the state of Sarawak, represent a complex and ecologically significant component of the terrestrial landscape. Sarawak accounts for over 60% of Malaysia's total peatland area, much of which comprises deep, fibrous, and sapric (amorphous) peat (M. Sa'don et al., 2015). These soils pose unique challenges in classification and engineering due to their high organic content, low shear strength, and high compressibility. Given the regional importance of these peatlands and their variability, reliable classification methods are critical for informed land management, agricultural planning, and infrastructure development.

Several classification systems have been developed for peat soils globally, ranging from lab-intensive taxonomies such as the USDA Soil Taxonomy to more field-oriented systems like the Von Post Humification Scale. Although each system has distinct theoretical underpinnings, their classification approaches vary substantially in how they treat the degree of humification, a critical factor for understanding peat decomposition, structure, and behaviour. Von Post classification system test is used to investigate the

degree of decomposition during the peat sampling. The von Post scale is a valuable tool for identifying peat based on its fibre content and the degree of humification or decomposition associated with it. Table 2.1 contains the Von Post categorization system for peat, as well as qualifying terms and symbols with descriptions (Huat, 2004).

While international systems provide comprehensive frameworks based on mineral composition, horizon development, and soil genesis, they often fall short in effectively categorizing tropical peat with high moisture and organic content typical of Malaysian lowlands (Khadijah Hajon et al., 2018). In contrast, the Von Post Humification Scale offers a practical and efficient approach for classifying peat soils in the field. As shown in Table 2.1, it categorizes peat from H1 (least decomposed) to H10 (most decomposed) based on visual and tactile assessments of colour, fiber structure, and the amount of water released when the sample is squeezed.

In Sarawak, where peat layers are often waterlogged, fibrous, and amorphous at greater depths, the Von Post scale remains a viable and commonly used method for initial classification (Kolay et al., 2010; M. Sa'don et al., 2016). Its main advantage is its simplicity and cost-efficiency, making it particularly suitable for remote areas such as Sarawak. However, the method is inherently subjective and lacks standardized quantitative metrics, limiting its broader analytical utility.

In contrast, under the USDA Soil Taxonomy, a globally recognized and systematic organic soil classification framework; Histosols are subdivided into suborders which is Fibrist (low decomposition, >75% fiber), Hemist (intermediate decomposition), and Saprist (high decomposition, <16% fiber), along with Folist (leaf litter) and Wassist (water-saturated) variants. This structure enables standardized categorization based on peat's fiber

content and decomposition status. While more standardized than Von Post, it is not specifically calibrated for tropical peat conditions, such as those in Sarawak, where fibrous and sapric peat layers are often intermixed, and high-water tables complicate sampling. Additionally, this system tends to favour laboratory-derived data, which may not always be feasible in remote or undeveloped peatlands.

The FAO/WRB (Food and Agriculture Organization of the United Nations) classification system (WRB, 2007), also recognizes organic soils but places more emphasis on horizon thickness, field texture, and land-use suitability than on the explicit degree of humification. Although this makes it versatile for global land classification, it fails to distinguish finely between decomposition stages, limiting its utility in studies concerned with peat behaviour under load, hydrology, or microbial activity.

The Esterle system (1990) was developed with a strong focus on peat-to-coal transformation. It assesses peat decomposition using laboratory-based indicators such as maceral composition, botanical origin, and coalification potential. While this system is effective for geological and stratigraphic applications, it is largely inapplicable for engineering or field-based ecological studies due to its complexity and need for advanced instrumentation. As such, its relevance to Malaysian peat research, especially in field applications in Sarawak, is minimal.

The classification framework developed by Wüst et al., (2003) represents a more holistic and tropical-specific approach. This system accounts for peat microstructure, hydrological regime, and vegetation input, offering an advanced perspective on tropical peat formation and ecology. However, its detailed micro-morphological and botanical requirements make it unsuitable for rapid field-based assessments or engineering

investigations. It remains highly valuable in ecological restoration and peatland carbon studies but is too elaborate for practical classification in geotechnical or agricultural development in Sarawak.

The Malaysian Soil Classification System (MS 1755:2004) for Engineering Purposes and Field Identification (Huat, 2004; Veloo et al., 2014) classifies peat based on its organic content and degree of humification a shown in Table 2.2. MS 1755:2004 provides a practical and nationally standardized framework for engineering and land development. It defines peat as a soil with at least 75% organic content by dry weight and a thickness of more than 30 cm. This standard is particularly useful for infrastructure development, foundation planning, and road alignment in coastal and inland peat regions like Kota Samarahan. However, it notably lacks categories for decomposition or humification and does not distinguish between fibric, hemic, and sapric peat, which limits its effectiveness in ecological or decomposition-sensitive analyses. Table 2.2 summarizes six prominent classification systems used in peatland studies: the Von Post System (1922), the World Reference Base (WRB) for Soil Resources, the USDA Soil Taxonomy (Soil Survey Staff, 1990), the Esterle System (1990), the Wüst et al. System (2003), and the Malaysian Soil Classification System (MS 1755:2004). On the other hand, while systems like USDA and WRB provide structure and global comparability, they do not offer the resolution or flexibility needed for tropical environments. Similarly, although the Wüst and Esterle systems contribute to the broader ecological and stratigraphic understanding of peatlands, they are too technical or narrow in scope to be implemented in routine site investigations or engineering studies in Sarawak.

In the context of Sarawak, and specifically the sapric peat of Kota Samarahan, the classification system must be both field adaptable and decomposition sensitive. The Von Post system fulfils this need more effectively than the other reviewed systems, enabling quick assessment of peat humification along vertical profiles that is an essential factor in geotechnical studies were peat behaviour changes significantly with depth. Despite its subjective nature, the Von Post scale remains the most practical tool for classifying tropical peat in East Malaysia, especially when complemented by laboratory validation such as fiber content and moisture content.

Overall, the comparative analysis reveals that no single classification system is fully sufficient on its own. The Von Post system, however, stands out for its practicality and relevance to tropical fieldwork, particularly in Malaysia's unique peatland environments. The lack of humification-specific guidance in the Malaysian Standard (MS 1755) further justifies integrating the Von Post scale into Malaysian peatland assessments. Current peat soil classification systems either lack specificity for tropical peat conditions or are too complex for practical engineering use in Sarawak. There is no integrated framework that combines field-adaptable humification assessment with quantitative geotechnical parameters. This study addresses this gap by applying the Von Post classification in sapric peat profiles and correlating it with laboratory-derived geotechnical properties to produce a more practical and regionally relevant characterization method.

Table 2.1: Von Post classification system (after Karlsson and Hansbo 1981)

Designation	Group	Description
Fibric (Fibrous peat)	H1	Completely undecomposed peat which releases almost clear water. Plant remains easily identifiable. No amorphous material present.
	H2	Almost completely undecomposed peat which releases clear or yellowish water. Plant remains still easily identifiable. No amorphous material present.
	H3	Very slightly decomposed peat which releases muddy brown water but for which no peat passes between the fingers. Plant remains still identifiable and no amorphous material present.
	H4	Slightly decomposed peat which, when squeezed, releases very muddy dark water. No peat is passed between the fingers, but the plant remains are slightly pasty and have lost some of their identifiable features.
Hemic (Semi-fibrous)	H5	Moderately decomposed peat which, when squeezed, releases very "muddy" water with a very small amount of amorphous granular peat escaping between the fingers. The structure of the plant remains is quite indistinct although it is still possible to recognize certain features. The residue is very pasty.
	H6	Moderately decomposed peats which have a very indistinct plant structure. When squeezed, about one-third of the peat escapes between the fingers. The structure is more distinct than before squeezing.
	H7	Highly decomposed peat. Contains a lot of amorphous material with very faintly recognizable plant structure. When squeezed, about one – half of the peat escapes between the fingers. The water, if any is released, is very dark and almost pasty.
Sapric (Amorphous)	H8	Very highly decomposed peat with large quantity of amorphous material with very indistinct plant structure. When squeezed, about two thirds of the peat escapes between the fingers. A small quantity of pasty water may be released. The plant material remaining in the hand consists of residues such as roots and fibers that resist decomposition.
	H9	Practically fully decomposed peat in which there is hardly any recognizable plant structure. When squeezed it is a uniform paste.

	H10	Completely decomposed peat with no discernible plant structure. When squeezed, all the wet peat escapes between the fingers.

Table 2.2: Malaysian soil classification systems (MSCS) for peat

Soil Group	Organic Content	Group Symbol	Subgroup Symbol	Degree of Humification	Subgroup Name	Field Identification
Peat	> 75%	Pt	Ptf	H1-H3	Fibric or fibrous	Dark brown to black in colour. Material has low density so seems light. Majority of mass is organic, so if peat is fibrous, the whole mass will be recognisable plant remains. If highly humified, the peat will be more likely to smell strongly.
			Pth	H4-H6	Hemic or moderately decomposed peat	
			Pta	H7-H10	Sapric or amorphous	

Table 2.3: Comparison of Peat Classification Systems

Classification System	Humification Focus	Key Criteria	Application Context	Strengths	Limitations
Von Post System (1922)	Direct, based on observable decomposition (H1 - H10 scale)	Color, fiber content, water expelled upon squeezing	Field-based, rapid peat decomposition estimation	Simple, cost-effective, widely used in field; suitable for tropical peat	Subjective and operator dependent; no quantitative benchmarks
US Soil Taxonomy (1990)	Indirect, inferred from fiber content and decomposition (Fibrist, Hemist, Saprist)	Fiber content and structure in laboratory conditions	Global taxonomy for soil surveys and ecological assessments	Standardized and detailed; used globally for soil taxonomy	Less suited to tropical peat diversity; requires lab analysis
WRB System (2006)	Moderate, based on organic horizon depth and field texture	Thickness of organic layer, texture, and use suitability	International land classification and use suitability	Versatile and recognized by global environmental agencies	Does not classify peat decomposition directly
Esterle System (1990)	High, detailed decomposition and botanical macerals (lab-based)	Degree of humification, coalification trends, botanical composition	Stratigraphic and paleoenvironmental reconstructions	Provides detailed stratigraphic and compositional insight	Complex and lab-intensive; not field-friendly
Wüst et al. System (2003)	High, considers peat microstructure, hydrology, and botanical input	Micro-morphology, hydrological regime, botanical indicators	Ecological research on tropical Peatland systems	Contextual, region-specific ecological understanding	Too detailed for standard field surveys or engineering use
Malaysian Soil Classification System (MS 1755:2004)	Low, focuses on organic content and thickness without humification categories	Organic matter content ≥75%, peat depth >30 cm	Engineering classification in Malaysia for development planning	Practical for construction and site investigation purposes	Ignores decomposition stage and humification classification

2.3 Soft Soil Stabilizations

Civil engineers have found that it is a challenging task to construct on peat soil due to its high compressibility. Construction on soft soils, such as peat soil, is typically associated with geotechnical problems and expenditures. Therefore, stabilising the peat is critical to overcome the issues. Soft soils, particularly peat and clayey soils prevalent in Malaysia, present substantial challenges in engineering and construction projects due to their high compressibility, low shear strength, and significant settlement potential (A. Wahab et al., 2020). The stabilization of these soil types is critical for ensuring structural integrity and minimizing economic losses associated with foundation failures and infrastructure deterioration.

2.3.1 Stabilization Method of Soft Soil

Peat soils, predominantly found in tropical lowlands, are characterized by high organic content, high compressibility, and very low shear strength. In Malaysia, and more critically in Sarawak, these problematic soils pose significant geotechnical challenges to infrastructure development. These vast peatlands are vital ecologically but problematic from an engineering perspective. Sarawak peat soils exhibit a high degree of variability in composition, fiber content, water content, and acidity compared to those in Peninsular Malaysia. The unique botanical origin and microclimatic influences have contributed to site-specific geotechnical behaviours, which render generalized stabilization approaches insufficient (Samuel & Evers, 2023). Therefore, soil stabilization may be a viable acceptable alternative for enhancing the geotechnical properties in such conditions (Nikookar et al., 2016; Patel & Patel, 2012). Peat stabilization has become a necessary focus for civil engineers seeking sustainable, economical, and site-specific solutions. It is a process of enhancing a soil's physical and engineering properties to meet predetermined

objectives and to fulfil the design criteria. The stabilization of peat soils, particularly in Malaysia and more specifically in Sarawak, remains an area of active research, with multiple studies providing insights into various methods and their effectiveness. A variety of techniques are employed, ranging from mechanical methods like compaction and preloading to chemical stabilization using additives (B. B. K. Huat et al., 2005).

Mechanical stabilization is based on increasing load-bearing capacity through compaction, preloading, or reinforcement using geosynthetics or deep soil mixing. Chemical stabilization, by contrast, relies on altering the physicochemical properties of soil through reactions with additives which typically involving pozzolanic reactions to form cementitious compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) (Falah & Muteb, 2023). However, the theoretical frameworks underlying peat stabilization practices often lack integration with the unique environmental and compositional contexts of Sarawak peat. Many studies take a standardized approach to test conditions without adequate consideration for local variations in soil structure, moisture content, and organic composition (Yulianto et al., 2022). There is a substantial gap in understanding relative to theory, methodology, and the incorporation of innovative materials to address the unique characteristics of peat in Sarawak. Sarawak peat presents theoretical contradictions where its acidity neutralizes or slows pozzolanic reactions, while its organic content impedes binder-soil contact. Thus, despite promising theoretical models, actual field performance frequently falls short unless modified stabilizers or hybrid methods are applied. This disconnects between theory and practice indicates the need for more region-specific scientific inquiry.

In Malaysia, various stabilization techniques tailored to Malaysian soil conditions have been emphasized, including mechanical methods (such as vibro-compaction) and chemical stabilization using additives like lime, cement, and environmentally friendly materials (Hauashdh et al., 2020; Yulianto et al., 2022). Recent studies primarily utilise chemical, biological, electrokinetic, and physical stabilisation techniques to enhance peat soil characteristics, including traditional cementitious binders and contemporary uses of industrial by-products like fly ash, silica fume, and eco-processed pozzolan (EPP). Traditional methods rely on theories of soil improvement that involve binder-soil interactions, load transfer mechanisms, and permeability reduction. Techniques such as preloading and deep soil mixing (DSM) aim to enhance load-bearing capacity through densification and drainage. Recent literature reveals variability in methodologies, with certain studies utilising basic mechanical stabilisation techniques and others incorporating advanced chemical mixtures. Furthermore, certain studies highlight chemical mechanisms, whereas others concentrate on biodegradable materials, indicating a division that may require integration to achieve a more unified comprehension of peat stabilisation dynamics.

Chemical stabilization methods are prevalent in Sarawak and involve the use of binders such as Ordinary Portland Cement (OPC), lime, fly ash, and more recently, silica fume and eco-processed pozzolan (EPP). While OPC remains the industry standard due to its reliable early strength gain, its effectiveness in acidic peat soils is limited. Cement stabilization shows initial success but suffers from long-term strength degradation in highly acidic Sarawak peats (Sutarno & Mohamad, 2023). Wong et al. (2009) reported strength improvements of over 100% when stabilizing Sarawak peat with OPC while Kolay & Rahman (2016) demonstrate that in Sarawak peat, humic acids react with calcium ions released during OPC hydration to form insoluble calcium-humic complexes. This

reaction inhibits both hydration and pozzolanic processes, impairing long-term stabilization effectiveness. Given the considerable carbon footprint associated with traditional cement-based stabilization, researchers have increasingly pursued eco-friendly alternative binders such as industrial by-products and biochar to mitigate environmental impact while maintaining or enhancing engineering performance (Hov et al., 2023). Newer materials like EPP and silica fume have shown improved microstructural integration and pozzolanic reactivity in soft soils. Comparative studies often yield inconsistent outcomes due to variations in experimental setups, peat characteristics, and additive compositions. Study by (Ahmad et al., 2023) have explored combining cement with industrial by-products, such as silica fume, to enhance stabilization while reducing carbon emissions. In his study, silica fume-treated peat improved UCS by over 40% compared to cement alone where high organic content disrupts pozzolanic reactions by preventing the effective bonding between soil particles and chemical additives. In contrast, Sutarno & Mohamad (2023) found only modest improvements in strength when stabilising peat with cement and similar additives. Significant strength gains were observed only with the application of higher doses of stabilisers and extended curing durations. The discrepancy between the two studies can be attributed to several critical factors, including peat heterogeneity (fibric versus amorphous), testing methods (laboratory versus field), and external conditions such as humidity and temperature.

Additionally, alkaline activators such as sodium hydroxide (NaOH) have demonstrated efficacy in neutralising peat acidity, which enhances cementitious reactions (H. M. Mohamad et al., 2023). NaOH has emerged as a potential additive that can neutralise peat acidity and create a chemically favourable environment for cementitious reactions. Despite the fact that there are still unresolved environmental hazards associated

with chemical leaching from NaOH use, H. M. Mohamad et al. (2023) reported substantial improvements in unconfined compressive strength (UCS) in NaOH treated peat. Consequently, the application of these methods to Sarawak peat requires careful consideration.

Chemical stabilisation techniques, particularly those that involve calcium silicate and alumina reactions, are intended to convert the amorphous organic matrix of peat into cementitious compounds. These models frequently overlook the significance of humic acids and the substantial water-retention properties of tropical peats, particularly those from Sarawak. Furthermore, a significant theoretical limitation in numerous studies is the assumption that peat exhibits uniform behaviour across different regions, resulting in an underestimation of Sarawak's peat properties that impede the effectiveness of standard binders (Ahmad et al., 2023).

Soft soil stabilisation aims to enhance strength and minimise settlement through modifications in soil structure and mineralogy. Mechanical techniques, including preloading and vertical drains, are designed to expedite consolidation. In contrast, chemical stabilisation employs pozzolanic reactions between soil and additives to generate cementitious compounds (Dehghanbanadaki et al., 2023). Biological methods, such as bio-cementation, are developing but are still in the experimental phase. Mechanical methods, including preloading with vertical drains, dynamic compaction, and geosynthetic reinforcement, are used to reduced settlement and accelerating consolidation. This method is widely employed in Peninsular Malaysia for soft clays (B. B. K. Huat et al., 2014). However, while partially successful in reducing settlement and accelerating consolidation, these techniques are less effective on Sarawak peat. Peat’s low permeability and high-

water absorption hinder pore pressure dissipation, resulting in prolonged consolidation times and limited strength gain. Multiple studies have confirmed that Sarawak peat undergoes substantial secondary settlement that persists well beyond the initial consolidation period. M. Sa'don et al. (2016) report non-linear creep beginning during primary consolidation, while H. M. Mohamad et al. (2021) document elevated secondary compression indexes and sustained post-loading settlement across field-relevant timescales. However, mechanical techniques such as vacuum preloading, have demonstrated effectiveness in consolidating peat layers and minimizing post-construction settlements.

Furthermore, biological methods, particularly bio-cementation, are emerging as sustainable alternatives for stabilizing soft soils. These methods, though promising, remain largely confined to laboratory research, with no documented full-scale applications in Sarawak to date (Dehghanbanadaki et al., 2023). At their core, such techniques harness microbial or enzymatic activity to induce mineral precipitation, effectively binding soil particles, reducing voids, and enhancing mechanical strength. Notable among these are microbial-induced calcite precipitation (MICP), enzyme-induced carbonate precipitation (EICP), and the use of bio-based polymers. Li et al. (2024) demonstrated that both MICP and EICP can significantly improve soil strength while reducing permeability. Further experimental work by Cheng et al. (2021) reported substantial gains in unconfined compressive strength (UCS) and decreased hydraulic conductivity in MICP-treated soft clays. SEM analysis confirmed that calcite precipitation contributed to particle bonding; however, treatment outcomes were found to be sensitive to microbial concentration and pH levels, posing challenges for consistent field application.

Similarly, Sharma & Ramkrishnan (2016) applied MICP to fine grained soils and observed that soil treated with bacteria and urea solution ($CaCl_2$) exhibited a fourfold increase in strength over untreated samples. Nonetheless, the researchers noted uneven distribution of calcite in larger-scale applications due to difficulties in nutrient transport through fine soils. While MICP used microbial-induced, EICP uses free urease enzymes to catalyse urea hydrolysis (enzyme-induced), forming carbonate ions that react with calcium to produce calcite that is similar to MICP but without the need for live microorganisms. A study by Mo et al. (2021) compared EICP and MICP in clayey soils and concluded that EICP offered greater control over reaction rates and improved homogeneity. Strength gains were comparable to MICP, but enzyme cost and degradation over time posed challenges to large-scale use. Another study by Zeitouny et al. (2023) showed that combining MICP with low doses of cement enhanced both UCS and durability while reducing the carbon footprint. SEM analysis revealed that calcium carbonate filled micro-voids, while cement formed C-S-H gel, reinforcing soil matrices. However, the interaction between organic matter in peat and hydration products remains unstudied and this hybrid approaches have not been tested on Sarawak peat. While EICP eliminates issues related to microbial survival, its cost and lack of long-term durability studies especially under Sarawak's humid tropical conditions highlight the need for localized evaluations.

Apart from that, biopolymers such as xanthan gum, guar gum, and alginate are gaining attention for their ability in biological method to bind soil particles and improve mechanical behaviour through natural polymerization. Mendonça et al. (2021) demonstrated that xanthan gum increased cohesion and reduced the permeability of soft clay soils. The treated soil showed enhanced resistance to wetting–drying cycles, making biopolymers viable for areas with high rainfall. However, the performance was found to

decline over time due to microbial degradation in the soil. In another study, Chen et al. (2022) applied a combination of biopolymers and fibers to enhance the durability and tensile strength of weak soils. The results indicated synergistic effects but also revealed challenges in cost optimization and long-term biodegradability. From the literatures, techniques such as MICP, EICP, and biopolymer have shown significant mechanical improvements and environmental benefits in various soft soil types. However, in Sarawak, biopolymer stabilization is underexplored for highly acidic and fibrous soils like Sarawak peat that present unique challenges. The potential interactions between organic soil constituents, microbes, and chemical additives remain uncharacterized, creating a barrier to practical application in local contexts.

Another method used in soil stabilization is Electrokinetic stabilization (EKS) which represents an innovative technique targeting moisture reduction and strength enhancement by applying voltage gradients. This method shows promising improvements in shear strength and moisture content reduction in Johor peat soils (A. Wahab et al., 2020). Physical reinforcement methods, such as air-tube grid systems, have been proposed to reduce settlement and vertical pressure in peat embankments, though these remain largely experimental and require further validation Md Talib et al. (2025). Electrokinetic studies apply different voltage gradients and durations, which affect the degree of moisture reduction and strength enhancement. While Electrokinetic stabilization shows unique benefits in moisture reduction and strength enhancement, which are not achievable by chemical methods alone, its application remains limited geographically and experimentally (A. Wahab et al., 2021).

Recent developments in ground improvement have shifted towards hybrid stabilization techniques that integrate multiple approaches to enhance overall performance. Combining microbial or biopolymer-based treatments with conventional binders such as cement, lime, or fly ash has gained attention for overcoming the limitations of biological methods, including slow reaction kinetics and susceptibility to environmental fluctuations (Ivanov & Chu, 2008). For instance, Rajakumar & Rao (2019) examined the stabilization of black cotton soil using 25% fly ash with various geogrid configurations. Their findings demonstrated that double-layer geogrid reinforcement significantly enhanced the California Bearing Ratio (CBR) under both soaked and unsoaked conditions. This improvement resulted in a significant decrease in required pavement thickness and presenting a more economical solution for highway infrastructure. Nonetheless, their investigation was confined to short-term CBR outcomes and did not address long-term settlement behaviour or material durability, which are critical for sustainable pavement design.

Furthermore, Deshmukh et al. (2019) studied the combination of fly ash with construction waste blends in pavement layers, improved by geogrid reinforcement to reduce critical tensile strain while controlling settlement. Their findings revealed that placing geogrid at the mid-depth of the base layer minimized settlement and reduced critical tensile strain. This study is significant for integrating laboratory and numerical validation; however, it did not isolate fly ash-cement as a treatment material. The effectiveness of hybrid methods depends significantly on careful optimisation that is customised to particular local soil properties. Kolay & Taib (2018) emphasized that results from comparative field trials remain inconsistent, largely due to the complex interactions between soil properties and stabilizing agents under real-world conditions. This

demonstrates the necessity for a deeper knowledge of these interactions to facilitate the development of effective design frameworks and predictive tools. Further research is crucial to establish comprehensive design guidelines and predictive models that effectively guide the use of hybrid stabilisation techniques in various soil types and environments.

A major strength of Malaysian research is its responsiveness to environmental and sustainability concerns. Several studies have evaluated waste-based binders (e.g., rice husk ash, EPP, scrap tire and fly ash) to reduce the environmental impact of stabilization work that aligns with national and global sustainability goals. The use of industrial by-products like fly ash, scrap tire and silica fume not only improve soil properties but also supports circular economy initiatives. Despite valuable contributions derived from the existing body of literature, significant theoretical, methodological, and practical gaps persist in the stabilization of peat soils, particularly in the unique conditions of Sarawak. The most significant research gap persists in the comparative analysis of traditional versus non-traditional stabilization materials, alongside insufficient exploration into synergistic effects when these materials are used in combination (A. Wahab et al., 2020). Future research should focus on comprehensive methodologies that involve local peat properties, innovative environmental solutions, and long-term performance metrics to ensure sustainable practices in peat stabilization. Furthermore, the incorporation of recycled materials such as crumb rubber could be crucial not only for engineering solutions but also for addressing environmental waste issues associated with construction practices.

While a range of stabilization techniques exists, their effectiveness is highly dependent on the unique properties of the underlying soil. Most existing research assumes a homogenous peat profile, ignoring the critical variability in Sarawak peatlands, such as

differences in humification and botanical origin, which can significantly affect stabilization outcomes. Most studies are also confined to short-term laboratory tests and rarely consider seasonal variability or long-term durability. Field-scale studies are limited and often lacking in reliable instrumentation for monitoring. While many previous studies on peat stabilization demonstrate important scientific caution, the majority remain limited to laboratory-scale investigations and have not successfully translated their findings into real-world field performance. These studies primarily rely on empirical data, which although valuable for initial evaluations, but fail to capture the complex and time-dependent interactions that occur under actual field conditions. Consequently, there is a pressing need to model the settlement behaviour of stabilized peat using established geotechnical software. Such modelling serves as an important bridge between laboratory testing and practical application, offering predictive capabilities that are essential for the safe and effective design of infrastructure on treated peat. Furthermore, many studies lack detailed microstructural analysis using techniques like scanning electron microscopy (SEM) or X-ray diffraction (XRD) to elucidate the stabilization mechanisms at the particle level, thus limiting the depth of understanding. Current research has demonstrated considerable creativity in experimenting with waste-based binders and hybrid models. However, theoretical assumptions often don't match the natural biochemical differences in peat, and inconsistencies in research methods make it difficult to reach a scientific agreement.

In conclusion, while the existing literature offers valuable insights into the mechanisms and methodologies for peat stabilization, substantial gaps remain concerning the integration of diverse stabilization approaches. Building a framework that incorporates both traditional and nontraditional additives; specifically targeting local environmental conditions will be crucial for enhancing the effectiveness of peat stabilization in Malaysia.

2.3.2 Traditional Stabilizer in Soft Soil Stabilization

Traditional stabilizers are commonly used as additives to strengthen weak soil and provide numerous benefits for soft soil stabilization. Over the years, there has been a growing number of studies examining the effectiveness of traditional stabilizers; primarily cement, lime, and fly ash in improving the engineering behaviour of problematic soils (Latifi, Horpibulsuk, et al., 2017b; Md Zahri & Zainorabidin, 2019). Guidelines for the application of traditional stabilisers and instructions for laboratory testing are available to ensure their effective use in geotechnical engineering practice. The usage has also been reported to neutralize acidity and strengthen many types of soil, particularly soft soil (B. B. K. Huat et al., 2005). Recent literature consistently supports that traditional stabilisers, such as cement and lime, enhance the mechanical properties of soft soils, particularly unconfined compressive strength (UCS) and shear strength.

Cement stabilized soils were discovered to be a reliable engineering alternative for meeting all the standards of sustainable infrastructure (Hambirao & Rakaraddi, 2014) and is widely available on the market. It is not only stabilized numerous types of soil, but nearly every problematic soil, such as clay and peat (Al-Bared et al., 2018; Kolay, Aminur, et al., 2011; Patel & Patel, 2012). For example, Hassan et al. (2019) observed a notable increase in shear strength parameters of organic soils in Mukah, Sarawak, when treated with a calcium-based stabilizer. The study's strength lies in its detailed analysis of strength development over a standard 28-day curing period, which provides baseline data for organic soil stabilization. However, the limitation of this study is its narrow scope where it primarily measured mechanical strength without considering long-term performance, durability under environmental cycles, or the chemical interaction between the stabilizer and the highly organic content of Sarawak peat. This issue has been previously noted, as

numerous stabilisation studies in Malaysia highlight short-term strength improvements while neglecting durability assessments beyond the initial curing phase, which poses challenges due to the dynamic characteristics of tropical soils. A study by Striprabu et al. (2018) focused on stabilizing clayey soil in Sarawak using class F fly ash. One of the notable strengths of this study is its clear documentation of dosage-effect relationships, showing that higher fly ash content led to increased strength. However, a weakness of the study is its reliance solely on physical strength tests without examining changes in soil microstructure, which would have helped in understanding the mechanism of stabilization more comprehensively.

One of the primary similarities among the studies mentioned above is that they all report a positive strength development after stabilisation, which confirms the fundamental effectiveness of traditional additives. However, the differences can be seen in the level of improvement and the effectiveness of various stabilisers across different soil conditions. For instance, Zakaria et al. (2022) compared conventional cement with a proprietary industrial stabilizer called Geocrete in the context of Sarawak peat. Their findings revealed that Geocrete outperformed cement in both strength and resistance to acid leaching, largely due to its better chemical compatibility with organic soils. This study's critical strength is its attempt to go beyond laboratory conditions by incorporating pilot field testing, which is rare in Malaysian soil stabilization research. However, the authors offered insufficient explanation of the chemical mechanism underlying Geocrete's performance, thereby reducing the reproducibility and scientific transferability of the findings.

Another important contribution came from Azam et al. (2024), who explored green stabilization using organic grout materials derived from agricultural waste. The study was

innovative in its environmental outlook and employed advanced microstructural techniques like SEM and FTIR to support its claims. While their approach successfully demonstrates reducing the compressibility and acceptable strength gains, the stabilizer's performance was still lower than traditional cement in highly saturated soil conditions. This finding highlights the basic conflict between environmental sustainability and mechanical performance, which is common in current literature.

When examine methodology across these studies, it becomes evident that inconsistent procedures often account for the differences in reported outcomes. Striprabu et al. (2018) adhered to conventional 28-day strength evaluation, while Azam et al. (2024) emphasized microstructural characterization over mechanical testing. These methodological variations limit the comparability of studies and present a gap in the development of a body of knowledge. Moreover, few studies attempt to standardize soil classification procedures or use consistent sample preparation techniques, which raises concerns about data reliability. Regional variability also plays a role in divergent outcomes. For example, Moayedi & Nazir (2018) observed that peat from Sarawak responded differently to lime and cement stabilization compared to similar soils in Peninsular Malaysia. They attributed these differences to the higher acidity and organic content in Sarawak peat, which inhibits the pozzolanic reactions that traditional stabilizers depend upon. This finding highlights the importance of site-specific investigations and cautions against overgeneralization based on results from other regions.

A common finding across studies is that chemical stabilizers such as OPC and lime significantly improve peat soil strength and bearing capacity, with UCS values increasing proportionally with stabilizer content and curing time. When dealing with traditional

stabilizers, it was normally necessary to allow for a reasonably long curing period and a substantial quantity of curing time (Makinda et al., 2018). The lengthy curing period was owing to the slow pozzolanic reaction, which generally takes 28 days to complete (Kalantari & Huat, 2009; Makinda et al., 2018; Teja et al., 2015). These two factors (time and material quantities) will have a direct impact on the construction cost and traditional stabilizers may also produce brittle behaviour in the soil as stated by Rahgozar & Saberian (2016) in their study. This will result in a weak foundation and structural failure. Another difficulty is that traditional stabilizers may change the pH of ground water.

According to Rahman et al. (2011), the strength of soil is improved by combining fly ash with lime or cement. However, this effect is only observed up to an optimal dosage which further additions may lead to the strength gains tend to plateau or even decrease. In most research, chemical stabilizer dosages differ widely, with OPC typically used in the range of 5-25%, lime at 2-12%, and fly ash up to 20%, and a combination with alkaline additives such as GeoCrete powder (GCP) to improve efficacy (M. A. Rahman et al., 2011). Rahmi et al. (2018) investigated cement stabilization by relating additive ratios to compressive strength results. Their study showed that systematic adjustments in cement content can significantly enhance strength, supporting the use of cement as a traditionally and effective preferred agent in stabilisation processes. Furthermore, the study also detailed how the enhancement of compressive strength in peat could be attributed to the formation of calcium silicate hydrates, which bind soil particles effectively, as noted in previous studies (Radwan et al., 2021; Wibisono et al., 2019). However, one significant limitation of their approach is the potential overlook of peat's unique organic composition, which may negatively influence the hydration process of cement when present in substantial amounts, resulting in inconsistent results across different types of peat. In

contrast, (H. M. Mohamad et al., 2023) highlighted the unique physicochemical properties of fibrous peat and its specific response to sodium hydroxide, indicating that the solution to peat stabilization may require a multifaceted approach that considers both traditional and nontraditional additives. The necessity to explore multifaceted stabilizers could enhance in understanding peat stabilization and potentially lead to more sustainable practices that consider both efficacy and environmental impacts.

Although Ordinary Portland Cement (OPC) is widely recognized for its high strength enhancement in soil stabilization, recent literature suggests that its effectiveness is influenced by a variety of contextual factors, particularly soil type, environmental conditions, and long-term durability. Several studies over the past five to seven years have consistently reported that OPC significantly improves the strength characteristics of soft soils, notably by increasing unconfined compressive strength (UCS) and reducing compressibility (Dehghanbanadaki et al., 2019; Rashid et al., 2018). This strength enhancement is primarily attributed to the formation of calcium silicate hydrates (C-S-H), which bind soil particles into a denser and more cohesive matrix.

One of the major strengths of using OPC is it widely recognized for its ability to rapidly enhance the load-bearing capacity of clayey and silty soils as demonstrated in a study of Rehman et al. (2025). Laboratory experiments consistently show substantial increases in unconfined compressive strength within just 28 days of curing. This makes OPC particularly attractive for time-sensitive construction projects. Similarly, Debnath & Dey (2018) highlighted its predictable behaviour and well-understood hydration mechanism, which makes it a reliable choice for geotechnical applications where uniformity and consistency are critical.

Al-Bared et al. (2019) in their study demonstrated that even small percentages of Ordinary Portland Cement (OPC) have been shown to significantly improve the strength and stiffness of soft clay subgrades, particularly in road construction applications. For instance, laboratory tests demonstrated that OPC additions as low as 4–6% substantially enhanced both unconfined compressive strength and stiffness characteristics of Malaysian soft clay. One of the major strengths of cement stabilization is its predictable behaviour, making it suitable for time-sensitive projects. However, this performance comes with caution. Moayedi & Nazir (2018) critically observed that in highly organic or acidic soils, such as those prevalent in Sarawak, the hydration process of cement is often hindered, leading to reduced strength gains or even structural degradation over time. Moreover, the high carbon footprint associated with cement production has increasingly drawn attention, especially in studies that prioritize environmental impact alongside mechanical performance. Furthermore, a growing body of recent literature has started to highlight the limitations and weaknesses associated with OPC use in soil stabilization. One significant concern is its reduced performance in soils with high organic content, such as peat soils common in Sarawak. Dehghanbanadaki et al. (2019) reported that while OPC was effective in sandy and clayey matrices, its stabilizing action was significantly compromised in acidic and organic-rich environments. This limitation comes from the fact that the high organic and acidic conditions inhibit the pozzolanic reactions necessary for OPC to develop strength. As a result, soils such as those found in Sarawak require either very high dosages of OPC or the inclusion of additives to achieve similar strength gains observed in mineral soils.

The findings across recent studies also show a degree of inconsistency in terms of OPC dosage, curing duration, and soil characteristics. For instance, while Golait & Padade

(2017) observed that 10–15% cement content significantly enhanced soil strength, Dehghanbanadaki et al. (2019) found diminishing returns beyond 8% content in highly plastic soils. These discrepancies suggest that OPC stabilization is highly context-dependent and that standardized dosage recommendations are difficult to establish without site-specific testing. While OPC remains a highly effective stabilizer known for its strength production, recent research has brought attention to its performance variability in organic and acidic soils, and the inconsistent results across different soil types and environmental settings. These findings emphasize the need for a more balanced approach where the mechanical advantages of OPC are weighed against its environmental drawbacks and site-specific limitations.

Among the traditional stabilizers, lime continues to be appreciated for its ability to reduce plasticity and improve workability, particularly in high-clay-content soils. According to Md Zahri & Zainorabidin (2019), lime treatment significantly improved the California Bearing Ratio (CBR) and reduced the plasticity index of soft clays in Peninsular Malaysia. This strength lies in lime's chemical reactivity with clay minerals, which promotes flocculation and pozzolanic bonding. However, this effectiveness is not universal. In soils with low clay activity or in organic-rich environments like Sarawak's peatlands, lime often fails to initiate sufficient pozzolanic reactions. Striprabu et al. (2018) found that lime stabilization of Sarawak clay required much higher dosages to achieve similar strength improvements observed in mineral soils, thereby raising concerns about cost-effectiveness and environmental sustainability.

In comparison, fly ash, particularly class F fly ash, has gained interest as a supplementary or partial replacement for cement and lime in recent years. Its pozzolanic

nature and industrial by-product status make it a potentially sustainable alternative. Striprabu et al. (2018) investigated the stabilization of Sarawak clay using class F fly ash and reported moderate strength gains, especially when used in combination with lime. A notable strength of fly ash is its environmental appeal; it reduces the need for high-carbon binders and repurposes industrial waste. However, the primary weakness identified in multiple studies is its dependence on the presence of sufficient calcium for activation. Without lime or cement, fly ash alone often produces limited improvements, especially in low reactivity soils. Furthermore, the study conducted by Azam et al. (2024) showed that the performance of fly ash in environments with in highly saturated or high peat material was less effective compared to traditional cementitious materials. This condition required extended curing periods and higher dosages to meet engineering standards.

What emerges from the literature is a consistent pattern where all three traditional stabilizers such as lime, cement, and fly ash demonstrate clear benefits in improving the engineering behaviour of problematic soils, but each comes with distinct limitations that are often magnified by local soil conditions and methodological decisions. However, the differences lie in how each stabilizer interacts chemically with specific soil constituents. Lime performs well with active clays due to ion exchange and pozzolanic reactions but underperforms in organic environments. Cement provides faster strength gains but may crack or degrade under wet-dry cycles if used in isolation. Fly ash, while sustainable, lacks binding strength unless paired with activators, and its long curing requirements make it less suitable for rapid construction timelines. A key similarity across recent studies is the acknowledgment that none of these materials is universally effective. For example, both Md Zahri & Zainorabidin (2019 and Tan et al. (2020) agree that cement and lime produce

impressive strength gains in silty clays, but struggle when applied to organic or fibrous peats.

Another notable critique emerging from the literature is the inconsistency in testing methods. While some studies employ comprehensive multi-day curing and microstructural analysis as Azam et al. (2024), others rely solely on short-term mechanical tests without evaluating long-term durability or chemical stability. This inconsistency makes it difficult to compare results across studies and prevent the development of standardized recommendations for field application.

In conclusion, while traditional stabilizers continue to play an essential role in Malaysian geotechnical engineering, recent research emphasizes the need for a more contextual and critical application of these materials. Moving forward, future studies should focus on hybrid stabilizer systems, region-specific formulations, and comprehensive testing protocols that reflect real-world conditions. Soil stabilisation practices in Malaysia, especially in Sarawak, can only evolve to meet engineering and environmental expectations through critical and integrative approaches.

2.3.3 Non-Traditional Stabilizer in Soft Soil Stabilization

Recognizing the environmental and economic limitations of traditional stabilizers, researchers in Malaysia, particularly in ecologically sensitive regions like Sarawak, have increasingly turned their attention to non-traditional alternatives for soft soil improvement. These methods aim to utilise waste materials, byproducts, and innovative chemical formulations that are comparable to or exceed traditional methods, while reducing environmental impact and enhancing sustainability. Non-traditional stabilizers including calcium-based industrial by-products, geopolymer binders, polymers, biomass silica, and

synthetic resins have emerged as innovative solutions. However, a critical assessment of recent literature reveals both promise and limitation in their application, largely dependent on theoretical grounding, experimental methodology, and site-specific soil behaviour.

Non-traditional additives have received increasing attention in recent years for soil stabilization due to their low cost, simplicity of application, short curing period, and lesser carbon dioxide emissions (Kua et al., 2016; Latifi et al., 2018). Previous research has shown that non-traditional additives can improve soil strength over time as studies done by Hassan et al. (2019); Moayedi & Nazir (2018) and Mohd Razali et al. (2018). Non-traditional additives are a chemically formulated stabilizer that differs slightly from traditional stabilizer. These stabilizers are frequently applied in a variety of fields, mainly in construction field. It is possible to define non-traditional stabilizer as a chemically formulated stabilizer or a modification of a traditional stabilizer. These stabilizers are categorized based on their primary chemical component as stated by Little & Nair (2009); Md Zahri & Zainorabidin (2019) and H. M. Mohamad et al. (2021).

Even though non-traditional stabilizers have disadvantages, the advantages outweigh the disadvantages, allowing research and study on these types of stabilizers to continue and develop. They provide solid reasons for using a non-traditional stabilizer as a soil stabilization agent. It can reduce the time required for the curing process, which is related to cost. Furthermore, it develops a ductile rather than brittle quality (Ayeldeen & Kitazume, 2017; Hamidi & Marandi, 2018). Furthermore, according to Kolay, Sii, et al. (2011) and Moayedi & Nazir (2018), non-traditional stabilizers are less harmful to the environment.

Due to their relatively low cost, ease of application, short curing time and lower carbon dioxide emissions, non-traditional stabilizers have been increasingly produced for soil stabilization purposes in recent years (Kua et al., 2016; Latifi, Eisazadeh, et al., 2017; Latifi, Horpibulsuk, et al., 2016; Latifi, Rashid, Marto, et al., 2016). A variety of companies are selling various kinds of chemical additives either in liquid or powder forms. However, the impacts of these products are not well known and their patented chemical composition makes it very difficult to determine and predict the stabilizing mechanisms (Wan Hassan et al., 2017).

A significant example of non-traditional stabilizer use in Sarawak is the study by Mustapa et al. (2021) which investigated gypsum-based stabilization of organic soils from Sarawak. While the findings showed improved strength and reduced compressibility, the study acknowledged that gypsum solubility in water poses durability concerns in high-rainfall environments like Sarawak. This highlights a common weakness in many non-traditional stabilization studies where while initial results are promising, the lack of long-term durability assessments under field-like tropical conditions raises questions about real-world applicability.

In recent years, synthetic and bio-based polymers have gained attention as non-traditional stabilizers for soft soil improvement, especially in regions with highly compressible and organic soils such as those found in Sarawak. Synthetic polymers, such as polyacrylamide (PAM), have shown promise in improving soil stability. As reported by (Chang et al., 2016), PAM acts by forming long molecular chains that bind soil particles together, thereby increasing cohesion, reducing permeability, and improving overall shear strength. This mechanism is particularly beneficial in fine-grained or erodible soils where structural integrity is otherwise weak. However, one of the primary limitations is that PAM

is sensitive to moisture variation where repeated wetting and drying cycles can decrease its binding capacity over time. Furthermore, some synthetic polymers such as PAM are not biodegradable and may raise environmental concerns if applied extensively without proper lifecycle analysis.

In response to these sustainability issues, researchers have turned to bio-based polymers as greener alternatives. One such material is chitosan; a natural polysaccharide derived from the exoskeletons of crustaceans. According to Amiri Tasuji et al. (2024), chitosan has been demonstrated to enhance soil aggregate stability and reduce hydraulic conductivity through its film-forming and adhesive properties. Unlike PAM, chitosan is biodegradable and non-toxic, making it more suitable for environmentally sensitive projects such as wetland rehabilitation or agricultural soil management. Despite these promising attributes, biopolymers like chitosan also come with challenges. Their performance under tropical conditions, such as high rainfall, acidic peat, and microbial decomposition has not been extensively evaluated. While lab-scale results are positive, there is a significant research gap in field-based assessments, especially within Sarawak's diverse soil environments. Furthermore, the cost and sourcing consistency of bio-based materials like chitosan remain barriers to widespread acceptance, especially in low-income infrastructure projects.

When comparing synthetic and bio-based polymers, a similarity across recent literature is the confirmation of their positive impact on soil structure, cohesion, and erosion resistance. However, the differences lie in mechanical durability versus environmental sustainability. Synthetic polymers like PAM offer high mechanical resilience but pose ecological risks, while bio-based polymers prioritize biodegradability at

the expense of long-term durability and cost-effectiveness. Few studies have directly compared these polymers under consistent soil and climate conditions, highlighting a methodological gap that must be addressed to generate practical and comparative data for engineering use.

In general, both synthetic and bio-based polymers represent a promising direction in non-traditional soil stabilization. However, their different performance characteristics and context-specific advantages call for integrated research models that balance mechanical, environmental, and economic considerations. Future research should focus on hybrid systems such as combining synthetic and bio-based additives and conduct long-term monitoring under real-world tropical conditions to evaluate performance consistency and ecological impact.

Another promising approach in nontraditional additives involves the use of urease enzymes to trigger a biochemical process known as Enzyme-Induced Carbonate Precipitation (EICP). As described by Arab (2019), urease catalyzes the hydrolysis of urea, which subsequently leads to the formation and precipitation of calcium carbonate ($CaCO_3$). These precipitates form mineral bridges between soil particles, thereby enhancing interparticle bonding, increasing strength, and reducing both permeability and compressibility. A clear strength of this technique is its adaptability to different soil types, including sands and low-cohesion silts, where traditional cementitious stabilizers may be less effective. Additionally, the precipitation of $CaCO_3$ can be finely controlled through the manipulation of reaction conditions such as pH, temperature, and enzyme concentration. Nonetheless, EICP has certain limitations where it has limited penetration depth in fine-grained or highly organic soils that is commonly found in Sarawak. The small pore spaces

in peat and high levels of organic acids can hinder carbonate crystal formation or dissolve existing precipitates. Moreover, the cost and stability of urease enzymes that often derived from plant or microbial sources can vary significantly depends on the storage conditions and batch preparation. These issues underscore a need for more rigorous field trials and cost-benefit analyses in tropical and high-moisture environments.

In addition to enzyme-based methods, a variety of bio-based and industrial by-product stabilizers have been investigated as alternatives to traditional cement and lime. Lignin and cellulose, extracted from biomass or agricultural residues, have shown potential to improve the plasticity, permeability, and strength of soft soils by acting as natural binders (Vaiana et al., 2021 and B. Yang et al., 2018). Their appeal lies mainly in their environmental benefits, as they are biodegradable, renewable, and often locally available as waste products. However, their chemical stability in wet tropical environments such as in Sarawak remains poorly documented, and the mechanical improvements reported in laboratory settings tend to be modest compared to synthetic binders or pozzolanic additives.

Industrial by-products such as slag and recycled concrete fines (RCF) represent another non-traditional stabilizer category with dual benefits which is reducing industrial waste while improving soil behaviour. For instance, ground granulated blast furnace slag (GGBS) has been shown to provide long-term pozzolanic reactivity when combined with alkaline activators. While studies like Jiang et al. (2018) have demonstrated strength improvements using slag-blended binders, most of this research has been conducted on sandy or clayey soils with moderate organic content. There is still limited data on their efficacy in organic-rich soils like peat, particularly under variable tropical weather conditions. Despite their varied chemical and environmental profiles, these non-traditional

stabilisers share similarities in the lack of consistent testing protocols and long-term performance data. Very few studies provide comparative assessments across multiple stabilizer types under the same soil and climate conditions. Furthermore, microstructural evaluations such as scanning electron microscopy (SEM) or X-ray diffraction (XRD) are often missing, which limits the mechanistic understanding of how these additives interact with soil constituents.

On the other hand, SH-85, a patented calcium-based additive, has received significant attention for its performance on problematic organic soils, including peat. As reported by Hassan et al. (2019)), the application of SH-85 resulted in a five to twenty-fold increment in unconfined compressive strength (UCS) compared to untreated peat. This substantial improvement was attributed to the high calcium content levels in the stabilizer, which promoted rapid ionic bonding and potential pozzolanic interactions with the silicates and aluminates present in the organic matrix. The strength of SH-85 lies in its ability to perform in acidic, organic-rich environments, such as Sarawak's fibrous peat soils, where traditional binders like cement often underperform due to inhibited pozzolanic activity. SH-85 reportedly achieves high early strength and maintains reasonable durability, making it attractive for road embankments, lightweight structures, and slope stabilization. However, a critical weakness in most SH-85 studies is the limited transparency regarding its chemical composition, as it is a commercial formulation. This limits the scope of independent replication and the development of a more comprehensive academic understanding of the material's reaction mechanisms.

In addition to calcium-based additives, agro-industrial waste materials have been investigated as non-traditional stabilisers, with a particular focus on addressing both

economic and environmental concerns. Palm oil fuel ash (POFA) is a widely explored material, representing a significant by-product of Malaysia's palm oil industry. Research conducted by (Mahmood et al. (2019) indicates that POFA, when used independently or blended with lime or cement, improves the UCS, CBR, and durability of soft soils. The pozzolanic reactivity of POFA, attributed to its high silica and alumina content that is crucial for strength development. A key strength of POFA is its availability and affordability, especially in palm-oil-producing regions like Sarawak. Despite these advantages, POFA's performance is not consistent across different soil types. Its reactivity depends on particle fineness, amorphous silica content, and the presence of activators, indicating variability in results across different batches. Furthermore, Mahmood et al. (2019) highlight the need for extended curing periods, frequently exceeding 28 days, to achieve optimum strength results. This constraint limits its applicability in fast-track construction environments.

Another locally abundant and increasingly studied alternative is biomass silica, which can be sourced from rice husk ash, sugarcane bagasse, or other agricultural residues. According to Hassan et al. (2019), biomass silica demonstrates promise due to its high pozzolanic potential and fine particle structure, which aids in filling soil voids and promoting denser packing. This material offers significant ecological advantages because it is renewable, diverting agricultural waste from landfills, and produces considerably lower CO_2 emissions than cement. However, the lack of standardization in biomass ash preparation, including inconsistent burning temperatures and ash purity, presents challenges for reliability and scalability.

In addition to solid additives, liquid-based stabilizers such as TX-85, a sodium silicate-based solution, have also been studied. TX-85, a non-traditional liquid stabilizer, has shown considerable promise in enhancing the engineering properties of problematic soils, particularly lateritic and soft subgrades common in tropical regions. TX-85 works by penetrating the soil matrix and chemically binding particles through gel formation (Latifi et al., 2013). TX-85 contributes to rapid strength development, improved soil structure, and environmental sustainability when applied either independently or when combined with PB-65 soil sealant and SH-85. Latifi et al. (2013) reported that the use of TX-85, in combination with SH-85, led to a four- to five-fold increase in unconfined compressive strength (UCS) within just seven days of curing. Their microstructural analysis revealed a denser soil matrix with fewer voids, indicating improved interparticle bonding and reduced permeability. Complementing these findings, Gupta & Singh (2020) demonstrated that incorporating 0.165% TX-85 with 5% SH-85 in the Pro-base system significantly improved the UCS of weak subgrade soils from 0.297 kg/cm² to 0.607 kg/cm² in 14 days. Additionally, the treated soils exhibited better moisture resistance and surface durability, making the system particularly suitable for rural road applications. Both studies highlight the cost-effectiveness and practical advantages of TX-85-based stabilization, especially in areas where conventional binders may be less feasible due to environmental or economic constraints. Although the short-term performance of TX-85 is encouraging, its long-term durability and effectiveness under field conditions, particularly in high-rainfall and moisture-variable environments like Sarawak, remain insufficiently explored. While international studies indicate its potential to reduce permeability and enhance stiffness, especially in lateritic soils, its application in Malaysia is still limited. The lack of field-based data and insufficient understanding of its chemical interactions with Sarawak's

organic-rich peat and clayey soils leave its broader applicability uncertain and in need of further investigation.

The study by M. H. Hassan et al. (2023) investigates the effectiveness of combining sodium silicate (TX-85) and biomass silica (SH-85) in stabilizing Batu Pahat soft clay, a problematic soil commonly found in parts of Malaysia. Their results showed that a mixture of 3% TX-85 and 9% SH-85 significantly improved the soil's plasticity characteristics by reducing the liquid limit and increasing the plastic limit, resulting in a lower plasticity index, attributed to the formation of cementitious gels that bonded soil particles. This change indicates improved workability and reduced moisture sensitivity. Unconfined compressive strength (UCS) also increased by more than tenfold within the first seven days of curing and continued to improve by day 28, suggesting rapid early-stage strength development. Furthermore, SEM analyses revealed a denser soil structure with fewer pores, while EDX confirmed the presence of additional silica that likely contributed to the formation of cementitious compounds. Consolidation tests further supported these findings by showing lower compressibility and swelling potential. These results align with findings from Latifi et al. (2013), who also reported improved strength and microstructure in lateritic soils treated with TX-85 and SH-85. Together, the evidence suggests that the use of the substance offers a viable, non-traditional alternative for soft soil stabilization in tropical regions, although long-term field validation remains necessary. Despite these promising results, the application of such materials to the specific context of Sarawak peat remains largely unexplored. As such, this study seeks to extend the application of sustainable stabilizers to regional soil types, enhancing local knowledge and offering scalable solutions for infrastructure development.

In summary, the integration of enzymatic, bio-based, and industrial by-product stabilizers presents a potential path toward more sustainable soil stabilization practices. These alternatives materials have demonstrated the ability to improve soil strength, reduce plasticity, and enhance microstructural bonding in soft and lateritic soils, as shown by the previous studies. However, their broader application remains limited by inconsistent performance across various soil types, a lack of clarity regarding reaction mechanisms, and minimal long-term field data, particularly under the humid, variable conditions of regions like Sarawak. Addressing these challenges requires future research to emphasise experimental comparisons, field-scale validation, and the integration of chemical, mechanical, and environmental performance metrics to support the responsible and efficient application of the innovative materials in soft soil stabilisation, particularly within the challenging geotechnical areas of Sarawak.

The review of current literature on non-traditional soil stabilizers reveals a significant disconnection between theoretical frameworks and practical applications, particularly when addressing problematic soils like Sarawak peat. Unlike traditional pozzolanic reactions that is common in cement or lime stabilization, non-traditional additives such as polymers or organic binders interact differently with soil, especially in acidic, organic-rich environments where calcium-based cementation is inhibited (Moayedi & Nazir, 2018). However, many studies still rely on traditional models to interpret results, leading to theoretical inconsistencies. Methodologically, research varies widely in terms of binder dosage, curing conditions, and strength assessment. Despite these shortcomings, most studies report strength and compressibility improvements using non-traditional materials such as studies by Azam et al. (2024) and Mustapa et al. (2021), although the results are highly dependent on soil type and stabilizer composition. However, significant

gaps persist in the examination of environmental impact, long-term durability, and leachate behaviour, accompanied by a lack of quantitative analysis regarding carbon footprint and soil stability in the context of tropical factors like flooding and peat fires.

Research on non-traditional soil stabilizers in Malaysia, particularly in Sarawak, has shown promising progress in addressing local geotechnical challenges through innovative and sustainable approaches. These efforts contribute to a growing body of knowledge aimed at improving soil behaviour using environmentally responsive materials. However, despite these advances, the literature remains fragmented in terms of testing methods, theoretical alignment, and long-term evaluation. A major limitation is the absence of standardized protocols, which compromises the reliability of cross-study comparisons and slows the development of practical guidelines for infrastructure applications. Moving forward, there is a clear need for research frameworks that combine microstructural analysis, field validation, and environmental performance metrics. Establishing such a standardized and multidisciplinary approach will be crucial for ensuring the safe, effective, and scalable use of non-traditional stabilizers in Malaysia's varied and challenging soil conditions.

2.3.4 Reinforcing Soft Soil by Using Scrap Tire

The reinforcement of peat soils using scrap tires presents a scientifically validated approach focused on mechanical enhancement rather than chemical stabilization. Unlike traditional chemical binders, tire-derived materials improve the soil's geotechnical behaviour through interlocking, lateral confinement, and stress redistribution. These mechanisms directly address peat's inherent limitations, namely high compressibility, low shear strength, and large void ratio by enhancing load transfer efficiency and deformation resistance.

In Sarawak, where extensive problematic peat soils inhibit infrastructure development, the utilization of recycled tires has attracted interest for its geotechnical benefits and environmental considerations. The accumulation of waste tires poses environmental risks, prompting efforts to repurpose them within civil engineering, particularly in soft soil stabilization. Scientifically, the relevance of tire-derived materials lies in their capacity to modify soil behaviour through mechanical interaction. Rubber inclusions physically engage with the soil matrix, enhancing strength and deformation properties via grain interlock, lateral confinement, and energy dissipation due to rubber's elasticity. These interactions increase ductility, post-peak resilience, and overall toughness of the stabilized mass.

Experimental investigations support these mechanisms. Mahyan et al. (2022) evaluated the inclusion of shredded rubber chips in Sarawak peat and reported significant improvements in unconfined compressive strength (UCS) and ductility. These gains were attributed to mechanical interlocking and the rubber’s capacity to absorb deformation energy. Their study also reinforced the theoretical position that tire particles function as tensile inclusions, offering lateral restraint in cohesionless or weakly cohesive soils. Edil & Bosscher (1994) similarly reported that shredded tires enhance stiffness and strength in granular soils by acting as stress-transmitting elements, confirming that improvements arise primarily from mechanical, rather than chemical, interactions.

Despite promising findings, the microstructural interface between soil and tire particles remains insufficiently characterized. Most studies, including Mahyan et al. (2022), lack detailed imaging techniques such as scanning electron microscopy (SEM), which could provide insight into interfacial contact, bonding behaviour, and pore-filling potential

at the microscopic scale. This limitation hinders comprehensive understanding of the reinforcement mechanism, especially under long-term loading conditions or in multi-additive systems.

The effect of tire particle size has also been critically evaluated. M. E. Mohamad et al. (2022) introduced finer crumb rubber into Malaysian peat and achieved more homogeneous distribution and compaction. However, this did not translate into superior strength performance compared to coarser rubber chips. The reduced interlocking efficiency of fine rubber particles may limit their effectiveness in fibrous, high-void soils like peat, where macro-void filling and structural bridging are critical. This implies that optimal particle size must be matched to the specific structural characteristics of the target soil, highlighting the need for design adaptability.

A hybrid stabilization technique was investigated by Razali et al. (2022), combining scrap rubber with melamine urea formaldehyde (MUF). This approach yielded synergistic benefits where mechanical reinforcement from rubber and chemical bonding from MUF resulting in improved strength and water resistance. However, concerns remain regarding the long-term environmental behaviour of MUF in tropical peat conditions, including potential chemical leaching or degradation. The proprietary nature of MUF formulations also limits scientific transparency and reproducibility.

Soil type compatibility further influences tire-based reinforcement efficacy. M. Sa'don et al. (2021) compared peat and clayey silt, demonstrating that rubber inclusions were more effective in the latter. The denser structure and higher cohesion of clayey silt offered better confinement, enhancing interfacial friction and stress transfer. This contrast

reinforces the importance of tailoring reinforcement strategies to specific soil types and their geomechanically responses.

Although multiple studies affirm the benefits of tire inclusions, particularly in enhancing ductility, energy absorption, and post-peak performance, there is a lack of standardization. Variations in rubber content (ranging from 5% to 20%), particle size, soil origin, and curing methods have produced inconsistent results. For example, Mahyan et al. (2022) achieved optimal performance at 15% rubber chip inclusion, while M. E. Mohamad et al. (2022) found diminishing returns beyond 10%. These discrepancies underscore the necessity for site-specific optimization frameworks and robust experimental controls.

In addition to mechanical enhancement, scrap tire particles have demonstrated secondary benefits. Prasad & Prasada Raju (2009) found that tire shreds improve subbase compaction and consolidation. Chan (2012) and Al-Bared et al. (2018) reported that tire rubber can fill soil voids, increase packing density, and facilitate improved load distribution. These outcomes suggest potential for broader geotechnical applications beyond peat alone.

In conclusion, the incorporation of scrap tire-derived materials into soft soil stabilization presents a dual advantage: geotechnical performance enhancement and environmental waste reduction. The literature clearly supports the role of tire rubber in improving strength, ductility, and deformation resistance through mechanical interlocking, confinement, and stress redistribution. Nonetheless, critical gaps remain, particularly regarding microstructural characterization and standardized design protocols. This study addresses these deficiencies by evaluating the mechanical and microstructural performance

of rubber-reinforced peat, in conjunction with both traditional and non-traditional stabilizers. By integrating strength testing with microanalysis, this research aims to establish a scientifically reliable framework for optimized peat stabilization in Sarawak's geotechnical context.

2.4 Mix Design and Proportion Determination

An effective mix design for peat soil stabilization must not only meet strength and durability requirements but also respond to the unique geotechnical challenges of high-organic-content soils like Sarawak's sapric peat. In this study, a hybrid stabilization strategy combining Ordinary Portland Cement (OPC), SH-85 chemical additive, and rubber waste (crumb and powder) was adopted. OPC remains a commonly used binder for soil stabilization due to its pozzolanic reactivity and ability to generate cementitious products that improve strength and stiffness. However, its performance in peat is often limited by the inhibitory effects of humic acids and high-water content. Several studies demonstrate that cement can still be effective at relatively low dosages when properly managed. Jumien et al. (2023) reported a substantial increase in unconfined compressive strength (UCS) from 47 to 684 kN/m² using only 5% OPC in combination with quarry dust, highlighting its adequacy for light-duty engineering applications such as parking lots or recreational surface. Similarly, Kolay et al. (2011) observed meaningful improvements in UCS and CBR with just 5% OPC in untreated Sarawak peat, indicating that low cement dosages can be sufficient under appropriate curing and moisture conditions.

Several studies have demonstrated that low dosages of Ordinary Portland Cement (OPC) in the range of 4–6% can still produce significant strength improvements in tropical peat soils. For example, Skels et al. (2013) reported that peat stabilized with 200–300

kg/m³ of OPC (equivalent to approximately 4–6% by weight) achieved up to a 20-fold increase in Unconfined Compressive Strength (UCS) compared to untreated samples, especially under surcharge and extended curing conditions. Similarly, Wong et al. (2008) found that a blend of OPC, ground granulated blast furnace slag (GGBFS), and siliceous sand could significantly enhance UCS while maintaining low cement content in the stabilization of tropical peat. These findings indicate that cement contents below 7% may be adequate when used with appropriate curing protocols and/or combined with supplementary materials.

However, it is equally important to note that other studies have cautioned against higher cement contents, as exceeding 10–12% may lead to excessive brittleness, reduced ductility, and increased environmental costs (Kohata et al., 2011; B. Yang et al., 2017). Therefore, a balance must be struck between strength gains and the potential drawbacks of over-stabilization, reinforcing the relevance of a 5% cement dosage as both effective and sustainable. From an environmental perspective, high cement usage also poses sustainability challenges. Radwan et al. (2021) noted that excessive reliance on cement in peat stabilization raises environmental concerns due to its carbon footprint and raw material demands. The study proposed a hybrid approach combining cement, fly ash, and polypropylene fibers, which not only maintained mechanical performance but also reduced environmental impact. Together, these findings underline the importance of optimizing, rather than maximizing the cement content in soil stabilization. Exceeding the effective threshold of approximately 10–12% cement may compromise mechanical flexibility and incur environmental and economic costs. As a result, stabilization mix design must carefully balance strength, ductility, and sustainability parameters.

To address the limitations of cement-only stabilization, non-traditional chemical additives such as SH-85 have gained interest due to their ability to accelerate strength gain and improve bonding at the microstructural level. SH-85 is a proprietary calcium-based liquid stabilizer that has shown rapid strength development and reduced porosity in soft soils. For instance, Hassan (2015) reported a UCS increase of over 300% in SH-85-treated peat samples within just seven days, attributing the improvement to enhanced flocculation and the formation of cementitious gels (N. Hassan et al., 2019). Latifi et al. (2016) provided further microstructural evidence through SEM analysis, showing denser particle packing and fewer voids in treated soils, which directly correlated with improved mechanical performance. However, despite its apparent effectiveness, SH-85 is under-represented in academic literature due to limited disclosure of its chemical formulation and a lack of long-term field validation. Its interaction with highly organic soils remains insufficiently studied, especially regarding environmental compatibility, reinforcing the need for more rigorous testing such as the microstructural validation incorporated in this study.

In parallel, the inclusion of recycled rubber materials such as crumb and powder from scrap tires has emerged as a sustainable method of improving ductility, toughness, and crack resistance in stabilized soils. Multiple studies support the beneficial effects of rubber additions, particularly in the range of 5–10%. M. Sa'don et al. (2018) found that incorporating 10% rubber crumb with 5% OPC in peat soil significantly enhanced ductility while maintaining satisfactory compressive strength. Mohamad et al. (2022) reported similar outcomes, noting improvements in UCS and deformation resistance when using waste tire rubber as a partial filler in soft soils. Further, SEM imaging presented by Wijeyesekera et al. (2016) revealed improved particle interlocking and void filling due to

the inclusion of rubber particles, which supported better load transfer through the stabilized matrix. However, researchers also caution that exceeding 15% rubber content can result in strength reductions due to poor adhesion between rubber and the cementitious matrix. The optimum content range therefore lies between 5% and 10%, which balances strength and ductility without compromising material integrity.

The present study develops ideas by employing a mixed design comprising 5% Ordinary Portland Cement (OPC), SH-85 at varying proportions (3%, 6%, 9%, and 12%), and rubber at 5%, 10%, and 15% to investigate the optimum mix design for Sarawak sapric peat. The selection is based on the past performance data and aims to address methodological gaps identified in prior research, such as inadequate microstructural validation, absence of hybrid mixes testing, and inconsistencies in performance criteria. The mix design process is additionally guided by the principles outlined in ACI 211.1 guideline (American Concrete Institute's standard practice for selecting proportions for normal, heavyweight, and mass concrete), adapted to suit the high moisture and organic content of tropical peat. Although originally developed for concrete applications, the systematic approach described in ACI 211.1 for selecting material proportions was adapted in this study to guide the optimization of binder and additive contents for peat soil stabilization. By following ACI's performance-based methodology that emphasizes strength, workability, and material compatibility, the mix design process in this research was structured through a series of trial batches using Ordinary Portland Cement, SH-85, rubber crumb and rubber powder. This approach ensured that the selected proportions were technically effective and tailored to the unique geotechnical characteristics of Sarawak sapric peat. The literature indicates that although individual components such as cement, SH-85, and rubber demonstrate potential when considered independently, their combined

effects in a well-optimized mixture provide the most effective solution for challenging peat stabilization work.

2.5 Mechanical Properties, Microstructure, and Numerical Modelling in Peat Stabilization

The stabilization of peat presents unique engineering challenges and as infrastructure expands into regions underlain by peat, it becomes increasingly critical to understand how fundamental geotechnical parameters such as compaction behaviour, California Bearing Ratio (CBR), and unconfined compressive strength (UCS) interact with soil chemistry and microstructure to influence mechanical performance. Compaction serves as the primary step in peat improvement, aiming to establish the optimum moisture content (OMC) and maximum dry density (MDD) that govern strength and deformation. Numerous studies have confirmed that reactive stabilizers such as ground granulated blast furnace slag (GGBS), recycled fine aggregates (RFA), and chemical additives like magnesium oxide (MgO) significantly improve compaction outcomes. For example, Yunus et al. (2023) demonstrated that incorporating GGBS in fibric peat reduced the OMC and increased the MDD, thereby enhancing repeatability and reducing susceptibility to water-induced weakening. Zhou et al. (2025) conducted a systematic laboratory study on red clay treated with various ratios of RFA and stabilizer, showing that the combination of 20% RFA with 20% stabilizer yielded the highest UCS values after 40 days of water immersion. These findings were attributed to the development of a dense reticulated structure, as observed through scanning electron microscopy (SEM), where hydration products encapsulated soil particles, resulting in the formation of strong particle networks.

Despite these advancements, considerable variability remains in reported compaction results. This variation is largely due to differences in peat fabric such as the

contrast between sapric and fibric types, the compaction energy levels (Standard versus Modified Proctor), and inconsistent control of critical test conditions such as curing humidity, mixing water content, and mould handling. These factors significantly affect the compaction peak and, consequently, the effectiveness of densification. Several studies lack documentation of these parameters, making inter-study comparisons unreliable (Lv et al., 2025). Although recent studies have improved in transparently reporting equipment and energy input, few are peat-specific or account for the fragile fibrous nature of organic soils that may collapse under standard handling.

One of the most pressing gaps is the lack of a standardized compaction protocol tailored to peat soils. Such a protocol must define the energy input, regulate water and humidity conditions, and establish a method for preserving peat structure during moulding and curing. Moreover, density metrics should be directly linked to stiffness parameters that can be used in subsequent settlement modelling, such as those required for SIGMA/W simulations (Ahmad et al., 2023).

Following compaction, the California Bearing Ratio (CBR) test is frequently employed to assess the load-bearing capacity of stabilized peat, particularly under soaked conditions that simulate in-service states. CBR values have consistently been shown to increase with binder content and curing time. For instance, Radwan et al. (2021) found that cementitious binders increased both soaked and unsoaked CBR values in peat subgrades. Pandey et al. (2025) confirmed that adding granular sub-base (GSB) material to expansive soils significantly improved CBR values, noting that Low Plasticity Clay (CL) soils required 12–16% GSB to meet standard thresholds, while Intermediate Plasticity Clay (CI) soils required 8–12%. However, variations in test methodology, such as compaction at

non-optimal moisture content or inconsistent soaking protocols, have led to discrepancies in reported CBR results. Some studies used constant water contents across different mixes, while others varied specimen geometry and penetration depths, introducing further inconsistencies.

Mechanistically, improvements in CBR are typically attributed to chemical bonding when using cementitious binders and to mechanical reinforcement when rubber particles are used. Razali et al. (2022) reported that moderate rubber content enhanced confinement and energy absorption, leading to increased soaked CBR values. However, excessive or overly fine rubber particles diluted binder efficacy, reducing resistance to penetration. These contradictory findings often stem from inadequate control over mix design or the lack of accompanying microstructural validation. Without techniques such as SEM or energy-dispersive X-ray spectroscopy (EDX), it remains unclear whether observed strength improvements are due to true bonding, compaction-induced densification, or mechanical interlocking. This methodological shortfall emphasizes the need for a peat-specific CBR protocol that not only prescribes compaction at OMC and MDD but also requires soaking at consistent depths and durations, along with validation through UCS and microstructural assessments. Only by triangulating data from these tests can one reliably attribute improvements to their underlying mechanisms.

The unconfined compressive strength test (UCS) remains one of the most widely used indices to assess undrained strength in stabilized peat. When binders such as ordinary Portland cement, carbide slag, coal gangue powder, and biopolymers like chitosan are used, UCS values tend to increase over time. Lv et al. (2025) found that Carbide Slag-Coal Gangue (CS–CG); which is two industrial by-products commonly used in soil stabilization

blends at a 70:30 ratio achieved UCS values exceeding 5 MPa after 28 days and retained nearly 4.8 MPa after six wet–dry cycles that suggesting an excellent durability. Hou et al. (2025) also observed that marine soils treated with MgO, and recycled aggregates achieved UCS values of up to 3 MPa while simultaneously sequestering CO_2, highlighting the dual environmental and mechanical benefits of such systems. Recent advances have also emphasized the development of sustainable alternatives to conventional stabilizers to reduce the environmental footprint of peat treatment. In this context, the use of agricultural and industrial by-products has gained considerable momentum. Abu Talib et al. (2024) demonstrated that incorporating 15% rice husk ash (RHA) as a partial replacement for Ordinary Portland Cement (OPC) significantly enhanced the unconfined compressive strength (UCS) of treated peat, achieving values of 580 kN/m² after 28 days of curing. SEM analysis revealed reduced porosity and denser particle packing, while energy-dispersive X-ray spectroscopy (EDX) confirmed an increase in calcium content, indicating the formation of calcium silicate hydrate (C-S-H) gels that played a pivotal role in strength development. This supports the view that bio-sourced pozzolans not only reduce cement usage but also contribute positively to microstructural evolution.

Khanday et al. (2023) further refined this approach by utilizing alkali-activated RHA-based binders enhanced with bauxite powder. Their study addressed multiple influencing parameters, including sodium hydroxide molarity, organic matter content, and binder-to-alkali ratios. The optimized combination of 20% binder content, 6M NaOH, A/B ratio of 0.7 yielded UCS values of 962 kPa in sapric peat, 873 kPa in fibric peat, and 668 kPa in hemic peat. The differences in performance across peat types were linked to variations in organic matter and fiber content, which affected gel penetration and curing

dynamics. Their findings reaffirm that proper chemical activation and material compatibility are essential for maximizing strength gains in highly organic soils.

From a field-engineering perspective, Basha et al. (2024) explored the use of sand cushions as an alternative stabilization method. Although not a chemical binder, the repeated compaction of reinforced sand cushions over peat layers effectively redistributed loads and minimized stress transfer to the underlying weak layer. Finite element simulations revealed improved stiffness and reduced settlement under cyclic loads, indirectly contributing to increased UCS-like response without requiring chemical admixtures. This approach offers promise for low-carbon geotechnical design in situations where material importation or chemical use is constrained. Complementing these laboratory and field studies, Muhardi et al. (2019) evaluated the performance of peat soil stabilized with varying blends of lime and Portland Composite Cement (PCC). A mixture containing 10% lime and 10% PCC was found to increase CBR to 26.5%, well above the typical subgrade threshold. While the study primarily focused on bearing capacity, the observed improvements in compactness and stiffness imply corresponding gains in UCS, especially when lime-induced pozzolanic reactions are active. The results highlight the synergetic effect of lime and cement in promoting both chemical bonding and strength uniformity across curing periods.

Collectively, these recent studies highlight the necessity for a mechanistic and context-specific strategy in peat stabilization. Strength development, as captured by UCS, is not merely a function of binder type or curing time, but rather the outcome of a complex interplay between binder chemistry, peat fabric, moisture conditions, and microstructural evolution. The integration of UCS testing with SEM and EDX analysis, as seen in these

recent works, allows for more rigorous interpretation of strength mechanisms and enhances confidence in design decisions. Future work must continue to refine UCS testing protocols by standardizing sample preparation, curing environments, and strain rate control, particularly in the presence of rubber or other modifiers that may alter the stress–strain response. In summary, the literature outlines various sustainable methods, including alkali activated binders, waste-based pozzolans, and physical reinforcement techniques, for improving the unconfined compressive strength (UCS) of peat soils. It also highlights the necessity for standardized, peat-specific protocols that combine mechanical testing with microstructural and durability evaluations.

To support the reliability of these sustainable stabilization methods, SEM and XRD analyses have been increasingly employed to validate the microstructural mechanisms underlying strength improvements, providing direct evidence of gel formation, pore refinement, and crystalline phase development that align with the mechanical gains observed in UCS testing. SEM and XRD analyses further revealed that these strength gains were due to the formation of calcium-aluminum-silicate-hydrate (C-A-S-H) gels and ettringite crystals, which filled voids and bound particles together. Similar findings by Ahmad et al. (2023) confirmed that strength improvements in stabilized peat were associated with visible reductions in pore size and improved cohesion at particle interfaces. Song et al. (2023) further demonstrated that humic acids in peat inhibit cement hydration, altering gel morphology and reducing bond continuity unless pH is properly managed. Hu et al. (2024) demonstrated that cyclic wetting and drying degrade cement stabilized soil matrices by increasing pore size and weakening the microstructure, which highlights the potential for durability loss under environmental fluctuations. Despite these insights, a major shortfall in the literature is the absence of standardized SEM–EDX procedures.

Varying magnifications, sample preparations, and analysis depths make it difficult to compare findings across studies. A defined imaging protocol is necessary for meaningful interpretation and for correlating UCS and CBR values with microstructural observations. While the literature shows clear progress in stabilizing tropical peat soils using chemical binders, mechanical additives, and microstructural validation, significant gaps remain. These include the lack of peat-specific protocols for compaction, CBR, and UCS testing; inconsistent control of critical variables such as moisture, pH, and curing; and a failure to fully integrate microstructural evidence with performance data.

The stabilization of soft subgrades, particularly those with high compressibility such as peat, has been a persistent challenge in geotechnical engineering. The use of advanced numerical modelling tools, including PLAXIS and GeoStudio, has facilitated more precise prediction of settlement performance by integrating laboratory-derived parameters into mechanistic simulations. This approach enables engineers to analyse not only the immediate improvement in strength but also the long-term deformation behaviour under realistic loading conditions. The objective of the present study, which is to analyse the settlement performance of an optimum design mixture for stabilized subgrade layers using GeoStudio, requires an understanding of how previous research has applied such numerical tools to similar problems, as well as a critical evaluation of their methodologies, theoretical underpinnings, and limitations.

GeoStudio, specifically its SLOPE/W and SEEP/W modules, has been applied in soil improvement projects to evaluate stability and consolidation performance after implementing ground improvement measures. For example, Fatmawati et al. (2023) investigated embankment stability on soft subgrades along a railway project in Indonesia.

They implemented prefabricated vertical drains (PVDs) combined with preloading to accelerate consolidation and increase shear strength, subsequently modelling stability in GeoStudio. The study demonstrated that the stability factors post-treatment ranged from 1.8 to 1.98, indicating safe conditions. The methodological strength of this research lies in combining field-derived settlement data with numerical stability analysis. However, it focused primarily on overall slope stability without explicitly modelling long-term settlement curves for varying material compositions, limiting its relevance to chemical stabilization scenarios. In contrast, PLAXIS-based studies often emphasize constitutive modelling and staged construction effects in settlement prediction. Gao et al. (2020) employed PLAXIS 2D to examine the settlement of soft subgrades reinforced with geogrid-encased stone columns and geocell-embedded sand cushions. Validation against field data confirmed the accuracy of the model, and the authors observed that reinforcement geometry significantly influenced settlement reduction. While the integration of field measurements strengthened the reliability of predictions, the absence of laboratory testing for chemically stabilized soils restricts direct applicability to subgrade mixtures optimized for strength and durability. Similarly, Ashiq et al. (2024) used PLAXIS 2D to assess the settlement performance of cement-stabilized soil layers in road embankments. Their model incorporated constitutive parameters derived from laboratory tests at varying cement contents and accounted for staged construction loading. They found that higher cement content significantly reduced long-term settlement and improved safety factors. A key advantage of their approach was the direct linkage between laboratory strength data and FEM settlement prediction. Nevertheless, the study did not explore microstructural mechanisms or the interaction between cement-treated soil and other stabilization techniques.

Some studies have addressed subgrade behaviour using GeoStudio methodologies for different soil conditions. Gunarti et al. (2024) evaluated the bearing capacity and deformation of subgrades stabilized with waste foundry sand (WFS) and fly ash (FA) layers. Although their primary focus was experimental, the results could be integrated into GeoStudio for predictive modelling under various traffic and environmental conditions. The strength of this study was in promoting sustainable stabilization methods, yet the absence of numerical settlement simulation leaves a gap in translating laboratory improvements into field-scale performance forecasts. In high-filled subgrade contexts, Liu et al. (2024) combined artificial neural networks (ANN) with genetic algorithms (GA) to predict settlement curves for cement-stabilized layers. The GA–ANN model provided more accurate predictions than standalone ANN, with a deviation of less than ±3 mm compared to measured values. This approach allowed for precise determination of the optimal paving time to avoid cracking in the stabilized layer. However, despite the strong predictive capability, the model was purely data-driven and lacked integration with mechanistic numerical tools such as GeoStudio or PLAXIS, thereby limiting its applicability for design-based simulations.

Other PLAXIS-based research, such as Siregar et al. (2024), focused on geotextile-reinforced embankments over peat soils. Their staged construction models closely matched consolidation settlement predictions from CPTu data, with differences of less than 3 cm over a 12-month monitoring period. This demonstrates the capability of FEM to account for time-dependent consolidation and reinforcement effects. Yet, like other reinforcement-focused studies, it does not address the performance of chemically stabilized subgrade mixtures, which is the central theme of the present research.

From the comparative analysis, the primary methodological differences are particularly in the choice of constitutive models, representation of boundary conditions, and extent of validation, an account for the variation in settlement predictions among these studies. GeoStudio applications tend to offer strong integration with seepage and consolidation processes but are often applied to mechanical reinforcement rather than chemical stabilization contexts. In contrast, PLAXIS models frequently incorporate advanced constitutive models such as Mohr–Coulomb and Hardening Soil, allowing for more realistic stress-strain simulations, though often without integration of optimal chemical stabilization mix designs. Studies that validate their numerical models using both laboratory and field data provide the most reliable settlement predictions, yet such dual-validation approaches are uncommon. The current research addresses this gap by directly incorporating laboratory-optimized stabilization mixtures into a GeoStudio settlement model, calibrated for site-specific subgrade conditions, to produce design-relevant performance predictions for stabilized subgrades in peat soil environments.

2.6 Executive Summary

Chapter 2 critically examined existing research and theoretical foundations relevant to the stabilization of peat soils, with a focus on mechanical enhancement through the incorporation of scrap tire materials, cement, and non-traditional stabilizers such as SH-85. The review began by establishing the engineering challenges of peat, including its high organic content, low shear strength, high compressibility, and acidic pH, all of which limit its suitability as a construction material without treatment.

A detailed discussion was presented on traditional stabilization techniques, notably cement-based methods, highlighting their effectiveness in strength improvement but also

their limitations in cost, environmental impact, and carbon footprint. This was followed by an evaluation of alternative and sustainable stabilization materials, including recycled rubber from scrap tires and bio-based additives, with emphasis on their potential to enhance ductility, reduce brittleness, and improve long-term durability.

The chapter also reviewed relevant mechanical performance indicators, such as Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), as well as microstructural analysis techniques (SEM and EDX) used to understand the underlying mechanisms of stabilization. Case studies and previous experimental findings were analyzed to identify performance benchmarks and optimum mix ranges for stabilized peat.

Finally, the literature review identified key research gaps: limited integration of waste-derived materials in multi-additive stabilization systems, insufficient long-term performance data, and lack of correlation between microstructural changes and mechanical improvements. These gaps provided the rationale for the present study, which aims to optimize peat stabilization by combining cement, SH-85, and scrap tire materials, and to validate the improvements through laboratory testing and numerical modelling.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

This chapter outlines the experimental and numerical procedures employed to investigate the strength optimization of stabilized peat using scrap tire material combined with traditional and non-traditional stabilizers. The research methodology is designed to meet the objectives stated in Chapter 1, involving sample collection, laboratory testing, microstructural analysis and numerical modelling using GeoStudio. The overall workflow is illustrated in a process flow chart shown in Figure 3.1.

The in-situ tests were also conducted such as Von Post Scale classification to investigate the degree of decomposition of the studied peat. The engineering property was also tested on both treated and untreated soil samples such as compaction by Standard Proctor, unconfined compression test (UCS) and California Bearing Ratio (CBR) test. The Scanning Electron Microscope (SEM) also conducted to evaluate the morphological and mechanical characteristics of the stabilized soil. An appropriate proportion of stabilizer that improves peat soil sample in term of strength and other engineering properties, had also been determined based on those conducted tests. The improvement in the soil strength of peat samples can be compared through tests that has been conducted on the control peat samples (untreated soil). The laboratory testing procedures of this study were carried out in accordance with British Standard (BS 1377: Part 2: 1990) unless stated otherwise. The experimental research focused mostly on laboratory testing to determine the important properties of peat and the suitable percentages or proportion of scrap tire as reinforcing agent and the additives used. It is into the study consideration that the mixture should be

applied economically to provide an effective strength stabilization of the peat. A flow chart summarizing the entire methodological sequence is presented in Figure 3.1.

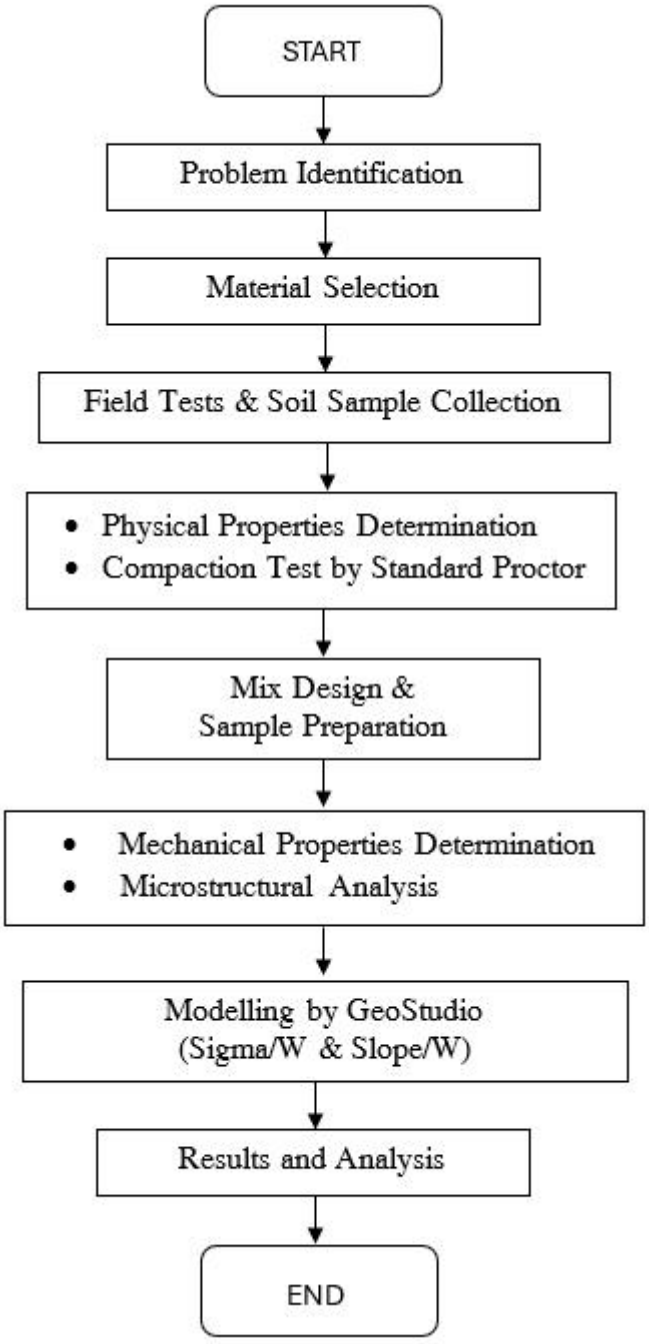


Figure 3.1: Flow Chart of the research study

3.2 Site Information and Sample Collection

A site visit was conducted to assess the condition of the peat soil and collect the soil samples for laboratory testing. The site investigations contributed to the assembling of general information about the formation and development of peats. The study site, as shown in Figure 3.2, is located at the peat swamp forest in Samarahan division. Figure 3.3 shows the site location that is located at Kampung Endap, Kota Samarahan, an area known for its extensive peatland and widespread pineapple cultivation. The region forms part of the Integrated Agricultural Development Area (IADA) and has been classified as moderately to severely degraded peat, primarily due to long-term agricultural use (Daud, 2009).

The selection of Kampung Endap as the study site was justified based on its unique environmental and agricultural characteristics. The area has been subjected to prolonged cultivation of shallow-root crops such as pineapple, which require extensive drainage. This process accelerates peat decomposition and oxidation, thereby altering the soil's physical and mechanical characteristics (Daud et al., 2012). The climatic conditions of Sarawak, characterised by high rainfall, persistent humidity, and elevated temperatures, are recognised as significant factors influencing peat formation, structure and degradation (Mohamad Tarmizi et al., 2013). These environmental factors directly influence the decomposition of organic matter, variations in the water table, and the consequent compressibility and instability of peats. Therefore, Kampung Endap presents a relevant and representative location for examining the efficacy of soil stabilisation techniques under actual tropical peatland environments.

The sample peats were collected on a sunny day, at 11.00 am, and the condition of the ground was very soft, and the ground water table was approximately 15 cm from the ground surface at the time of sample collection. The top vegetation was preliminarily cleared to remove unwanted grass and roots from the upper soil layer. To obtain the samples for this study, disturbed soil samples were collected by excavation of trial pits, as shown in Figure 3.4, and taken from a depth of 0.3 to 1 m below the ground surface. Samples were immediately sealed in an airtight container to preserve their moisture and structure during transport to the laboratory. For tests requiring dry samples such as moisture content and organic content analysis, the peat was oven-dried at 105°C for 24 hours, as per ASTM D2216. Then, the samples were dried directly under sunlight and were subsequently crushed and sieved to the desired size before further testing for the basic properties and mechanical testing.

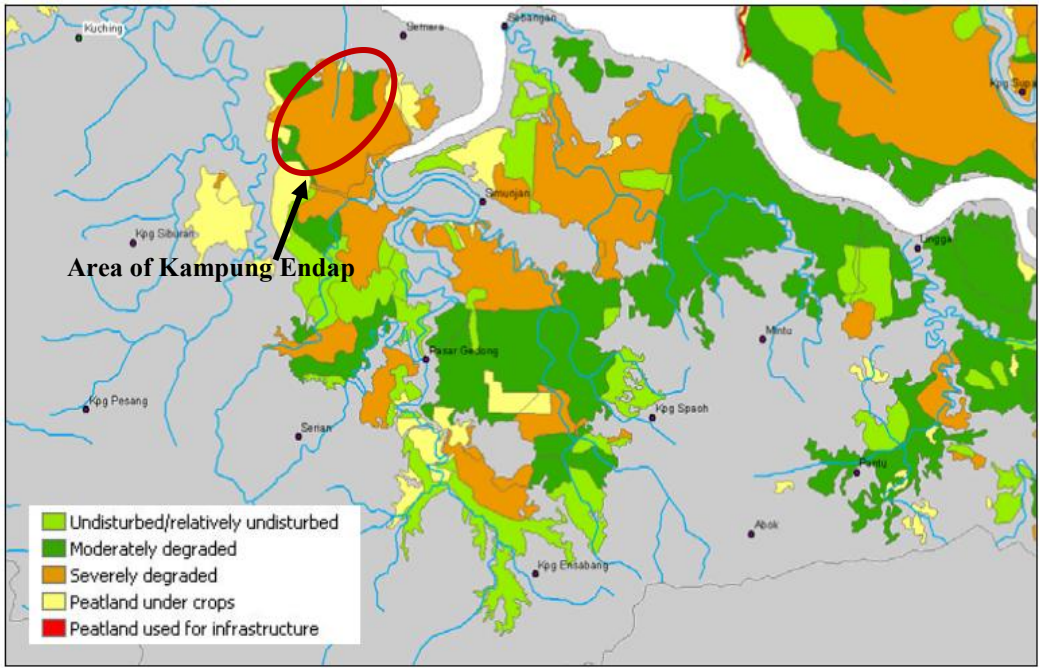


Figure 3.2: Distribution and status of peat swamp forest in Samarahan Division (Davies et al., 2010)



Figure 3.3: Location of sampling at Kg. Endap, Kota Samarahan



Figure 3.4: Peat at sampling site

3.3 Materials

There are five main materials used in this study to develop the design mixtures that meet the objectives of the study such as peat, cement, shredded rubber crumb, rubber powder and calcium-based resin, SH-85, respectively.

3.3.1 Peat

The peat used in this study was dark brown and fibrous collected from Kampung Endap in Kota Samarahan as indicated in Table 3.5. It exhibited a natural moisture content of 580.2%, a specific gravity of 1.67, and a highly acidic pH of 3.00. The organic content was extremely high at 86.83%, while the ash content and fiber content were measured at 13.17% and 94.5%, respectively. Results obtained confirming its soft, porous, and highly

compressible nature. The type of peat to be stabilized in this study is sapric/ amorphous peat. The soil was classified as sapric peat using the Von Post humification scale, with a rating of H8, indicating an advanced state of decomposition and a predominantly amorphous organic structure. During the test, about two-thirds of the peat had escaped between the fingers and released a very small quantity of pasty water when squeezed. The overall texture of the peat also can be seen in a relatively homogenous paste. The visual classification of the test conducted is shown in Figure 3.5. This classification is critical, as sapric peats generally possess lower shear strength, reduced permeability, and a high tendency for long-term settlement compared to less decomposed fibric peats (B. B. K. Huat et al., 2014).

The in-situ shear strength of undisturbed peat was assessed using a field vane shear apparatus, in accordance with BS 1377: Part 9 (1990). The test was conducted at shallow depths (0.5 - 1.5 m) immediately upon sample collection to avoid moisture loss and disturbance. The vane was inserted vertically into the undisturbed peat and rotated at a modest rotation rate of 6° to 12° per minute until failure. Peak shear strength was recorded, with values ranging from 9 to 19 kPa, indicating the extremely weak and soft nature of the native peat. This test is particularly appropriate for fibrous and saturated soils such as tropical peat, where traditional shear testing is often impractical.

The Atterberg limit was determined using the cone penetrometer method as recommended for highly organic soils, producing an exceptionally high liquid limit (LL) of 434%. This further confirms the extreme plasticity and instability of the natural peat. Due to the excessive moisture and organic matter, the plastic limit (PL) could not be reliably determined, and the plasticity index (PI) was inferred to be extremely high based on field

behaviour and LL data. These geotechnical characteristics justify the selection of peat as a critical focus for soft soil stabilization, given its widespread occurrence in Malaysian lowlands and its well-known problems for construction; namely low bearing capacity, high settlement, and poor workability (B. B. K. Huat et al., 2014; Zainorabidin & Wijeyesekera, 2007b).



Figure 3.5: Von Post Scale Classification (Sapric peat, H8)

Table 3.1: Physical and Engineering Properties of Untreated Peat Soil

Peat Soil Parameter	Value
Natural Moisture Content (%)	580.20
Specific Gravity (Gs)	1.67
Organic Content (%)	86.83
Fiber Content (%)	11.98
Ash Content (%)	13.17
pH Value	3.00
Liquid Limit (LL, %)	434
Plastic Limit (PL, %)	Not Determined
Plasticity Index (PI, %)	Highly Plastic
Vane Shear (kPa)	9 – 19
Soil Classification	H8 (Sapric)

3.3.2 Ordinary Portland Cement (OPC)

Cement is a typical traditional additive used in soil stabilization as its compromising effect in stabilization and reducing the construction cost. Studies have shown that there is a significant improvement in soil that can be achieved by using cement as the stabilizing agent. The improvement is due to the chemical reaction called hydration when the soil is combined with water and causes the soil-cement mixture to harden. This hardening process cemented the soil particles together, increasing the soil bearing capacity, thus making cement as an effective soil stabilizer.

In this study, Ordinary Portland Cement (OPC) was used as traditional stabilizer. It was sourced from a local supplier and used at a constant dosage of 5% by dry weight of peat. The utilization of OPC will enhance the hydration process in the peat mixture due to the presence of organic matter and low pH of peat that tends to interfere with the hydration process. Furthermore, with its low pH value, the acidic nature of the peat will interact with the calcium released during cement hydrolysis that will form an insoluble calcium humic acid. This causes a decrease in calcium crystallization that results in an increase in the peat-cement mixture strength.

The type of cement that used in this study was Ordinary Portland Cement (OPC) Type 1 from Cahya Mata Sarawak (CMS) Sdn. Bhd. as shown in Figure 3.6. The physical properties and chemical compositions of this OPC Type 1 manufactured by CMS Sdn. Bhd. are shown in Table 3.2. These include bulk density, specific gravity, and chemical oxides such as SiO_2, Al_2O_3, Fe_2O_3, and CaO, all of which are essential parameters in determining cement reactivity and strength gain potential in peat stabilization applications. These properties are critical in evaluating the cement's effectiveness as a stabilizing agent, as high calcium oxide (CaO) content promotes pozzolanic reactions with organic matter,

while specific gravity and particle fineness influence the workability, strength development, and durability of the stabilized peat matrix.



Figure 3.6: OPC type 1 used in the study

Table 3.2: Physical properties and chemical compositions of OPC Type 1

Ordinary Portland Cement (OPC) Type 1		
Physical Properties	Bulk Density	1.2 – 1.4 kg/L
	Specific gravity	3.15
	Retained on 45 μm sieve	18%
	Retained on 90 μm sieve	2%
Chemical Composition (%)	Silicon dioxide, SiO_2	19.34
	Aluminum oxide, Al_2O_3	5.20
	Ferric oxide, Fe_2O_3	3.41
	Sulphur trioxide, SO_3	2.85
	Magnesium oxide, MgO	1.44
	Potassium oxide, K_2O	0.47
	Calcium oxide, CaO	64.75
	Sodium oxide, Na_2O	0.10
	Loss on ignition, LOI	3.42
	Free CaO	1.39
	Total Alkali	0.41

3.3.3 Processed Scrap tyre: Shredded Rubber Crumb and Rubber Powder

The processed scrap tire that acts as fibre reinforcement material in this study is shown in Figure 3.7. This material was provided by ZHA Environmental Sdn. Bhd. A mechanical grinding machine is used to process the scrap tire, which has been classified according to the required size. The reinforcing wire of the scrap tire was removed first before being converted into rubber crumbs (RC) (1-4 mm particle size), rubber powder (RP) (<1 mm particle size) and fibre polyester.

RC exhibits a particle size ranging from 0.5 mm to 4.75 mm, characterized by a rough and fibrous surface texture. In contrast, RP is a finer material with a particle size typically between 30 and 80 mesh (<0.6 mm). The bulk density of RC ranges from 0.5 to 0.9 g/cm³, while RP is denser, ranging from 0.9 to 1.1 g/cm³ (Bekhiti et al., 2014; Siddique & Naik, 2004). The size of shredded rubber crumb used in this study is ranging from 1-5 mm and rubber powder is in the range of 0.08-1.6 mm which is classified as a fine material. The amount of the reinforcing materials was controlled at 5%, 10% and 15% of dry weight of peat. The performance of stabilized soil incorporating recycled rubber materials depends significantly on the physical and chemical characteristics of the shredded rubber crumb and rubber powder used. These properties affect their interaction with soil particles and chemical binders such as cement or pozzolanic materials. However, the company does not publicly provide a technical data sheet for the processed scrap tire. Therefore, relevant characteristics are compiled from reliable, peer-reviewed literature that reflects industry-accepted ranges for similar materials. Studies by Liu et al. (2020) and Z. Yang et al. (2020) provide comprehensive descriptions of particle size distribution, density, chemical structure, and surface morphology of recycled rubber materials used in geotechnical and

asphalt applications. The physical differences between RC and RP result in distinct interaction behaviours with soil particles. The coarse and fibrous nature of RC allows for enhanced mechanical interlocking, making it effective in improving soil structure and reducing settlement. However, RP, due to its finer texture and higher surface area, promotes uniform dispersion and may be more reactive in systems involving cementitious or pozzolanic binders (L. Liu et al., 2020). Both materials share similar chemical compositions, predominantly consisting of hydrocarbons, sulfur-based crosslinking agents, carbon black, and zinc oxide (ZnO). However, as stated by Mohamad Tarmizi (2014) and Shahidan et al. (2021); RP is noted for its more homogeneous composition, which enhances consistency in performance when used in fine-grained or reactive soil systems. These parameters are critical in evaluating the effectiveness of rubber additives in improving shear strength, reducing compressibility, and enhancing ductility in soft soil stabilization. Table 3.3 summarizes the typical values and observed behaviour of shredded rubber crumb and rubber powder based on the cited literature.

Table 3.3: Typical Physical and Chemical Characteristics of Recycled Rubber Materials

Property	Rubber Crumb	Rubber Powder	Reference
Particle Size	0.5 mm – 4.75 mm	30–80 mesh (<0.6 mm)	(Aman et al., 2021; J. Liu et al., 2024)
Bulk Density	0.5 g/cm³ – 0.9 g/cm³	0.9 – 1.1	(Shahidan et al., 2021; Z. Yang et al., 2020)
Surface Texture	Rough, fibrous	Smooth or porous (after treatment)	(Chen et al., 2022; L. Liu et al., 2020; Z. Yang et al., 2020)
Chemical Composition	Alkanes, alkenes, sulfur compounds, ZnO, carbon black	Similar composition; more homogeneous	(Mohamad Tarmizi, 2014; Shahidan et al., 2021)
Softening Temperature	~180–220 °C	~160–200 °C	(Aman et al., 2021; L. Liu et al., 2020)



(a) Shredded Rubber



(b) Rubber Powder

Figure 3.7: Processed Scrap Tire

Recycled crumb rubber typically softens between 160 and 220 °C during mixing processes, with finer rubber powders exhibiting similar softening temperatures. These observations, drawn from industry-reviewed literature by Lo Presti (2013), reflect the material behaviour under elevated temperature conditions. These thermal properties are crucial when rubber particles are used in hot-mix applications or environments with elevated temperatures. Literature indicates that both RC and RP have demonstrated success in improving various soil parameters such as unconfined compressive strength (UCS), compaction characteristics, and long-term settlement behaviour. However, the effectiveness is context dependent. RC is more suited to improving mechanical behaviour through increased ductility and energy absorption, particularly under dynamic loads or expansive soils. In contrast, RP has shown better integration in chemically stabilized systems, where its fine particles interact synergistically with cementitious compounds to form denser matrices (Naseem et al., 2019). Some studies have identified challenges; despite the advantages they have demonstrated. The size variability of RC may result in non-uniformity in mix design, while RP's lubricating effect may reduce compaction

efficiency at large dosages. However, current literature lacks comprehensive comparisons of RC and RP in combination with non-traditional binders (e.g., eggshell powder, biomass silica) for the stabilization of peat, particularly under tropical climatic conditions like those in Sarawak. Most existing studies focus either on mineral soils or asphalt applications. Thus, the incorporation of both RC and RP in this study is intended to bridge this gap, allowing for a comparative evaluation of mechanical and microstructural outcomes using UCS, CBR, and SEM/EDX analyses.

3.3.4 Biomass Silica– Calcium based Resin (SH-85)

Presently, various types of non-traditional additives are available in the market, either in a liquid or powder form. In this study, to enhance the engineering properties of the peat soil in the study area, a non-traditional calcium-based stabilizer (SH-85) in powder-type, is used as a stabilizer (Figure 3.8). SH-85 is a bio-technological waste and is supplied by Probase Manufacturing Sdn Bhd, a local company based in Johor Bahru, Johor. The product is a biotechnological innovation made from biomass silica waste to creates 'artificial laterite' in the treated soil matrix to meet the mechanical and structural requirements of the geotechnical design. SH-85 is a finely powdered material derived from biomass silica sources; most commonly rice husk ash and combined with calcium-based compounds to induce pozzolanic reactions in soft soils. Although its full proprietary formulation is not publicly disclosed, several peer-reviewed investigations have characterized its primary constituents and behaviour, underlying mechanisms in soil improvement, particularly for organic and tropical residual soils. As example, Marto et al. (2014) had performed a test with the Energy Dispersive X-Ray Spectrometer (EDAX) machine, which revealed the general elemental composition of the SH-85. Their findings indicate that the SH-85 material consisted mostly of calcium oxide, with a proportion of

68.21%, followed by aluminium oxide (Al_2O_3) at 12.30%, carbon dioxide (CO_2) at 10.24%, and silicon dioxide (SiO_2) at 9.25%, as detailed in Table 3.4. These oxides are recognized for their role in developing cementitious phases such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), both of which are essential to achieving matrix densification and strength gain during the curing phase (N. Hassan et al., 2019).

In addition to its chemical composition, SH-85 exhibits a high alkalinity, with a pH value of 12.65 at a liquid-to-solid ratio of 2.5. This elevated pH facilitates the dissolution of silica and alumina from the soil, further accelerating the pozzolanic reaction and formation of binding gels that contribute to structural integrity as found by Latifi, Eisazadeh, et al. (2017). While the specific bulk density of SH-85 was not measured in this study, prior works have reported that biomass silica-based powders generally fall within the range of 1.0–1.3 g/cm³.

The SH-85 additive was incorporated into the soil at varying dosages of 3%, 6%, 9%, and 12% by dry weight. Its inclusion has been shown to significantly promote cohesion among particles and reduce the compressibility of peat, primarily through the development of s



Figure 3.8: Calcium based stabilizer (SH-85)

Table 3.4: Chemical composition of SH-85 (Latifi, Eisazadeh, et al., 2017)

Properties	Percentage (%)
CaO	68.21
Al_2O_3	12.30
CO_2	10.24
SiO_2	9.25
pH (L/S = 2.5)	12.65

3.4 Sample Preparations

The peat soil samples used in this study were collected in a peat deposit area in Kampung Endap, Kota Samarahan, Sarawak. The peat soil samples were then dried directly under sunlight before being crushed by a mechanical equipment and sieved to a size finer than 2 mm. In this study, the treated reinforced peat was analysed based on the Unconfined Compressive Strength (UCS) test, and the California Bearing ratio test (CBR) at designated samples preparation and curing methods and were prepared at Geotechnical Laboratory in UNIMAS.

To perform the Standard Proctor, UCS and CBR tests, grinded samples were sieved by using a 5 mm test sieve and 425 μm test sieve respectively. The dried peat was then subsequently mixed homogenously by manual with the desired percentage of shredded rubber crumb or rubber powder for at least 3 to 5 minutes after water addition. It must be clear that all the specimens were prepared at their intended optimum moisture content (OMC) and maximum dry density (MDD). It is to ensure that all the added materials were evenly distributed. The specified amount of cement and resin was then added to the mix for samples preparation. After that, the samples were wrapped in a thin plastic film and cured

for 7, 28 and 56 days for UCS whereas the design mix for CBR were kept in its mould for 7- and 28-days prior testing. Both UCS and CBR soil specimens were prepared for soaked and unsoaked condition. On the other hand, the control samples of untreated peat and peat-cement mix were also prepared for comparison purposes. All specimens were prepared in a single batch mixing to ensure the homogenous of the soil mixture and a total of three (3) specimens for each design mix were prepared.

The design mix in this study consists of peat (Pt), cement (C), shredded rubber crumb (RC), rubber powder (RP) and a powdered resin. The dry peat sample at its optimum moisture content (OMC) and maximum dry density (MDD) was reinforcing with rubber crumb and rubber powder and treated with non-traditional additives; a biomass silica calcium-based powdered resin namely as SH-85. The addition of shredded rubber crumb and rubber powder which is a non-active additive agent act as fibre reinforcement in the mix design. Fibre reinforcement is added to promote the soil particle cohesion and to act as a structural mesh that bonds the soil together to increase soil structural stability. The percentages added were 5%, 10% and 15% of the total mass of the mixture dry weight with and without the addition of cement. Ordinary Portland Cement (OPC) also added in this study to act as the bonding agent to stabilize the peat soil at a controlled percentage of 5% from the dry weight of peat. As for SH-85 resin, different percentages are added, starting at 3% and increasing to 6%, 9% and 12% based on the dry weight of the peat soil. Table 3.5 shows the complete design mixtures in this study.

Table 3.5: Design mix of fiber-reinforced material

Sample ID	Peat (%)	Cement (%)	SH85 (%)	Rubber Powder (RP) (%)	Rubber Crumb (RC) (%)	Description

Pt only	100	0	0	0	0	Control (untreated)
Pt + 5% C	95	5	0	0	0	Cement only
Pt + 3% SH-85	97	0	3	0	0	
Pt + 6% SH-85	94	0	6	0	0	
Pt + 9% SH-85	91	0	9	0	0	
Pt + 12% SH-85	88	0	12	0	0	
Pt + 5%C + 5% RC	90	5	0	0	5	
Pt + 5%C + 10% RC	75	5	0	0	10	
Pt + 5%C + 15% RC	80	5	0	0	15	
Pt + 5%C + 5% RP	90	5	0	5	0	
Pt + 5%C + 10% RP	75	5	0	10	0	
Pt + 5%C + 15% RP	80	5	0	15	0	
Pt + 5%C + 5% RC + 3% SH-85	87	5	3	0	5	Stabilized samples
Pt + 5%C + 5% RC + 6% SH-85	84	5	6	0	5	
Pt + 5%C + 5% RC + 9% SH-85	81	5	9	0	5	
Pt + 5%C + 5% RC + 12% SH-85	78	5	12	0	5	
Pt + 5%C + 10% RC + 3% SH-85	87	5	3	0	10	
Pt + 5%C + 10% RC + 6% SH-85	84	5	6	0	10	
Pt + 5%C + 10% RC + 9% SH-85	81	5	9	0	10	
Pt + 5%C + 10% RC + 12% SH-85	78	5	12	0	10	
Pt + 5%C + 15% RC + 3% SH-85	87	5	3	0	15	
Pt + 5%C + 15% RC + 6% SH-85	84	5	6	0	15	
Pt + 5%C + 15% RC + 9% SH-85	81	5	9	0	15	
Pt + 5%C + 15% RC + 12% SH-85	78	5	12	0	15	

Table 3.5 continued

Pt + 5%C + 5% RP + 3% SH-85	87	5	3	5	0	
Pt + 5%C + 5% RP + 6% SH-85	84	5	6	5	0	
Pt + 5%C + 5% RP + 9% SH-85	81	5	9	5	0	
Pt + 5%C + 5% RP + 12% SH-85	78	5	12	5	0	
Pt + 5%C + 10% RP + 3% SH-85	87	5	3	10	0	
Pt + 5%C + 10% RP + 6% SH-85	84	5	6	10	0	Stabilized samples
Pt + 5%C + 10% RP + 9% SH-85	81	5	9	10	0	
Pt + 5%C + 10% RP + 12% SH-85	78	5	12	10	0	
Pt + 5%C + 15% RP + 3% SH-85	87	5	3	15	0	
Pt + 5%C + 15% RP + 6% SH-85	84	5	6	15	0	
Pt + 5%C + 15% RP + 9% SH-85	81	5	9	15	0	
Pt + 5%C + 15% RP + 12% SH-85	78	5	12	15	0	

3.5 Basic Properties Determination

The laboratory works is done to determine the physical and strength properties of the reinforced peat by several experiments such as compaction by Standard Proctor test, Unconfined Compression (UCS) test, California Bearing Ratio (CBR) test, and Scanning Electron Microscope (SEM). To assess the basic characteristics of the peat soil; physical and index properties such as Atterberg limits (liquid limit, plastic limit and plasticity index), specific gravity, pH, moisture content, organic content and fiber content were determined. There are two (2) phases for the laboratory works for this study:

i. The physical and basic properties of the peat soil,

ii. The strength optimization of the stabilized reinforced peat soil.

The physical properties tests were conducted through laboratory works to determine the physical and index properties of the treated and untreated peat soil. These tests consist of moisture content, specific gravity, soil pH, organic content, fiber content and Atterberg limit (liquid limit, plastic limit & plasticity index). The determination of the dry density and the optimum moisture content of treated and untreated peat are determined by Standard Proctor test. Furthermore, the engineering properties were determined by unconfined compression (UCS) test to investigate the strength gained by the reinforced peat specimens. In this test, the strength of both treated and untreated (control) peat soil samples were compared. The strength test was carried out on peat soil samples that has been cured for 7, 28 and 56 days, respectively.

3.5.1 Moisture Content

Water is present in most soil naturally, especially peat soil. Water is inherently present in nearly all natural soils, with peat soils exhibiting particularly high moisture content due to their organic and porous nature. Moisture content is a fundamental parameter in geotechnical investigations because it significantly influences the compressibility, shear strength, and overall mechanical behaviour of soft soils such as peat (B. B. K. Huat et al., 2005; Kazemian et al., 2011a). It is defined as the ratio of the mass of water to the mass of dry soil solids, typically expressed as a percentage. The moisture content, which is represented as a proportion of the dry solid particles, has a significant impact on soil behaviour.

In this study, the moisture content of peat samples was determined in accordance with British Standard BS 1377: Part 2: 1990, which is a widely accepted standard for geotechnical testing procedures. The procedure involves drying a representative soil sample in a thermostatically controlled oven at a temperature of 105–110°C for 24 hours, after which the mass of water lost is measured relative to the dry soil mass. A soil is considered ‘dry’ when no additional moisture can be removed under these standard drying conditions. The test was conducted using a calibrated laboratory drying oven (Model: UTD-1310 UTEST), which was calibrated prior to use with a digital thermometer and traceable calibration certificate in accordance with BS1377 standards. Each test was repeated in triplicate to ensure repeatability, and average values were recorded. The heating period of 24 hours was chosen to ensure full moisture evaporation, especially given the high water-retention capacity of peat. Advantages of this method include its simplicity, reproducibility, and conformity to international testing standards, providing high confidence in comparative data. However, one limitation is that certain organic volatiles or

chemically bound water might also be lost during drying, potentially leading to a slight overestimation of moisture content in organic soils like peat. Despite this, the method remains as the standard baseline for moisture determination in geotechnical engineering due to its balance of accuracy and practicality. According to the standard procedure (BS 1377: Part 2: 1990 - Methods of Test for Soils for Civil Engineering Purposes: Classification Tests), a representative sample of wet soil was first obtained and weighed in a clean, dry, and pre-weighed moisture content tin as shown in Figure 3.9. The initial mass of the tin and wet soil was recorded with an accuracy of 0.001 g. The tin containing the soil was then placed in a thermostatically controlled oven maintained at a temperature of 105 ± 5°C and left for a minimum duration of 24 hours, or until a constant mass was achieved. After drying, the tin was removed from the oven, allowed to cool in a desiccator to prevent moisture absorption, and subsequently reweighed. The mass of water lost was calculated by the difference between the wet and dry soil masses, while the dry mass of soil was used as the reference for determining the moisture content. The moisture content (w) was calculated using the formula:

Equation 3.1

$$\boldsymbol{w} = \frac{\boldsymbol{m_1 - m_2}}{\boldsymbol{m_3 - m_1}} \times 100\%$$

Where,

w = moisture content (%)

m_1 = mass of container (g)

m_2 = mass of container and wet soil (g),

m_3 = mass of container and dry soil (g)



Figure 3.9: Moisture content determination

This test was conducted in triplicate for each soil sample to ensure repeatability and accuracy of results. All weighing procedures were performed using a digital electronic precision balance Shinko Denshi FX300i (model AJ320E) with 0.001 g sensitivity, which had been calibrated prior to the testing sequence according to BS1377 requirements. The method offers a simple and reliable means of determining the moisture content of soils and is considered suitable for routine geotechnical investigations. However, in organic soils like peat, volatile organics may evaporate during oven drying, potentially leading to a slight overestimation of moisture content. This limitation is noted in BS 1377: Part 2: 1990 and should be considered in interpreting results for high-organic content soils.

3.5.2 Specific Gravity

The specific gravity test is critical for computing soil parameters such as void ratio and density. Its primary advantage lies in its precision for small sample volumes and its

suitability for organic soils. However, its limitation in peat testing is the risk of underestimation due to air entrapment and floating organic particles. These limitations were mitigated through standardized de-airing procedures and repeated measurements to ensure consistency.

The specific gravity test of peat in this study was based on the procedures outlined in BS 1337: Part 2: 1990. In this study, pycnometer method is used to determine specific gravity of the soil samples. Specific gravity (Gs) is an important soil test that represents the value of particle density to the density of water. However, in the case of peat soil, the ratio of the peat sample to the density of kerosene is used. A small pycnometer bottles were filled with approximately 20 g of dry peat that had been passing through a 425 μm test sieve and kerosene was poured into the bottle until the sample was slightly covered as shown in Figure 3.10. The bottles were then placed in a vacuum desiccator for at least 1 hour. The pycnometer, along with its contents, was weighed to determine the volume of displaced kerosene, which was used to calculate specific gravity.

The weighing process was performed using a digital analytical balance (ADAM LBH15) with a precision of ±0.01 g. This balance was calibrated weekly using traceable standard calibration weights. Tests were conducted in triplicate to enhance measurement reliability, and the average of those tests was determined to minimize errors and ensure the accuracy. The specific gravity (Gs) determination is calculated using the following equation:

$$G_s = \frac{m_2 - m_1}{(m_2 - m_1) - (m_3 - m_2)} \qquad \text{Equation 3.2}$$

Where,

G_s = specific gravity of peat

m_1 = mass of bottle and stopper (g)

m_2 = mass of bottle, stopper and dry peat (g)

m_3 = mass of bottle, stopper, soil and kerosene (g)

m_4 = mass of bottle, stopper when full of kerosene only (g)



(a) Vacuum desiccator (b) Sample in a pycnometer fill with kerosene

Figure 3.10: Specific gravity apparatus

3.5.3 Soil pH

The measurement of pH is a fundamental parameter in geotechnical investigations, especially for peat soils, as it directly influences the chemical behaviour of the soil and its compatibility with stabilizing agents such as lime, cement, and other chemical binders (Kazemian et al., 2011a). The pH test serves as an indicator of the acidity or alkalinity of the soil, which governs the reactivity of pozzolanic additives and, consequently, the stabilization efficiency.

In this study, the pH of both untreated and chemically treated peat samples was measured to evaluate the changes in soil alkalinity due to the addition of various stabilizers. For the untreated wet peat, pore water was extracted by manually squeezing the soil to obtain sufficient moisture for immediate pH assessment. For the air-dried samples, the test was conducted in accordance with BS 1377: Part 3: 1990, Clause 9.2, which is the standardized method for determining the pH of soil-water suspensions.

Approximately 30–35 grams of representative dry peat soil were obtained by air-drying the samples at ambient room temperature and sieving them through a 2.00 mm test sieve to ensure consistency in particle size. Subsequently, 75 mL of deionized distilled water was added to the soil in a clean 250 mL glass beaker, and the mixture was stirred gently for several minutes using a glass rod. The suspension was allowed to equilibrate undisturbed for at least 8 hours to ensure full interaction between soil particles and the water phase. Before measurement, the suspension was stirred again to homogenize the sample. The pH of the resulting solution was measured using a calibrated laboratory digital pH meter (Model: Accumet AB150) as shown in Figure 3.11. The device was equipped with a combined glass electrode and a built-in temperature probe, linked to a voltage display. The meter was calibrated prior to each testing session using three standard buffer solutions (pH 4.0, 7.0, and 10.0), following manufacturer guidelines and laboratory quality assurance procedures to maintain measurement accuracy within ±0.01 pH units.

Advantages of this test include its simplicity, rapid execution, and minimal sample preparation, making it suitable for both field and laboratory applications. However, limitations exist when dealing with highly organic soils such as peat, where colloidal activity and microbial degradation may cause pH fluctuations over time. To mitigate this,

all pH measurements were taken immediately after homogenization and conducted in triplicate to ensure reliability and consistency of results.

The pH results provide valuable insights into the initial chemical environment of the soil and the extent of alkalinity shift following stabilization. This information is crucial for understanding the effectiveness of stabilizing agents and for optimizing mix designs in peat stabilization projects.



Figure 3.11: Digital pH meter

3.5.4 Organic Content

The determination of organic matter content is fundamental for the classification of peat and other organic soils, as it significantly influences their engineering behaviour. Organic matter affects key geotechnical properties such as shear strength, compressibility, bulk density, and soil structure, and governs the soil's moisture retention capacity and chemical reactivity with stabilizing agents (B. B. K. Huat et al., 2005; Kazemian et al., 2011a).

In this study, the organic content of the peat samples was determined using the loss-on-ignition (LOI) method as prescribed in ASTM D2974-87 (Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils). This method quantifies organic matter as the mass of combustible content relative to the dry mass of the soil sample. The procedure began by oven-drying the peat samples at 105 ± 5°C for 24 hours, using a calibrated laboratory drying oven (Model: UTD-1310 UTEST) to remove all physically bound moisture. Calibration of the oven was carried out monthly using a certified digital thermometer with traceable calibration. Once fully dried and cooled in a desiccator to prevent atmospheric moisture absorption, the samples were weighed using a Shinko Denshi FX300i (model AJ320E) with sensitivity ±0.001 g, which had been calibrated weekly using traceable standard weights.

Subsequently, the samples were transferred into pre-weighed porcelain crucibles as shown in Figure 3.12 and ignited in a muffle furnace (Carbolite Gero) at a constant temperature of 440 ± 25°C for a minimum duration of four hours or until a constant weight was achieved, indicating complete combustion of the organic fraction. Calibration of the furnace was conducted biannually using a certified thermocouple. After ignition, the crucibles were cooled in a desiccator and reweighed to determine the residual ash content. The organic matter content was calculated as the difference between the oven-dry mass and the post-ignition mass of the sample, expressed as a percentage of the oven-dried mass, using the following equation:

$$\text{Ash Content}, D = \frac{C \times 100}{B} \qquad \text{Equation 3.3}$$

$$\text{Organic Content} = 100 - D \qquad \text{Equation 3.4}$$

Where,

B = weight of oven dried sample (g)

C = weight of ash (g)

D = ash content (%)



(a) Sample in crucibles (b) Sample in a furnace

Figure 3.12: Organic content apparatus

3.5.5 Fiber Content

The fiber content of peat soil is a fundamental parameter that influences the soil's engineering behaviour, including its compressibility, shear strength, and hydrological characteristics. High fiber content is typically associated with greater water retention, lower bulk density, and anisotropic strength behaviour, which necessitates proper classification and characterization in geotechnical applications (ASTM, 2013). In this study, the determination of fiber content was conducted according to the procedures

outlined in the ASTM D1997-13: Standard Test Method for Laboratory Determination of Fiber Content of Peat Samples by Dry Mass. This method provides a reliable estimation of the mass percentage of fibrous organic material relative to the total dry mass of the soil and is particularly appropriate for tropical peats such as those found in Malaysia and Sarawak.

Approximately 100 g of air-dried peat was selected and weighed using a calibrated digital balance (±0.001 g accuracy). The soil sample was transferred to a 1000 mL glass beaker, and 500 mL of a 5% sodium hexametaphosphate dispersing solution was added as shown in Figure 3.13 (a). This chemical agent facilitates the breakdown of soil aggregates without damaging organic fibers. The mixture was initially stirred using a magnetic stirrer for five minutes and then left to stand undisturbed for 15 hours to allow full chemical disaggregation. After settling, the solution was agitated again using a mechanical laboratory stirrer for an additional 10 minutes to ensure complete dispersion. The suspension was then poured over a 150 μm stainless steel sieve, and the effluent was safely discarded via a laboratory sink with appropriate waste management protocols. The retained material on the sieve was gently washed with low-pressure distilled water to avoid damaging or dislodging delicate fibrous particles. The rinsing continued until the outflowing water appeared clear, indicating the removal of fine particles and dispersants. To eliminate carbonates, the retained material was immersed in 2% hydrochloric acid (HCl) for 10 minutes as shown in Figure 3.13 (b). It was then thoroughly rinsed with distilled water to remove any residual acid and inorganic contaminants. Any remaining coarse mineral grains or plant detritus such as roots or wood fragments were manually removed using non-metallic tweezers to avoid mass bias.

Subsequently, as shown in Figure 3.13 (c), the contents were transferred to a filter paper of known weight, held in a Büchner funnel attached to a vacuum flask to ensure effective transfer. The filter paper containing the fibrous material was then placed in a ventilated laboratory oven set at 105 ± 5°C for a minimum of 24 hours or until a constant mass was recorded, ensuring full dehydration of the fibers. The sample of dried sample is shown in Figure 3.13(d). The final mass was used to compute the fiber content percentage using the following formula:

$$\text{Fiber Content (\%)} = \frac{M_{\text{fiber}}}{M_{\text{initial dry}}} \times 100 \qquad \text{Equation 3.5}$$

Where,

$M_{\text{fiber}} =$ oven − dried mass of retained fibers

$M_{initial\,dry} =$ initial oven − dried mass of soil sample

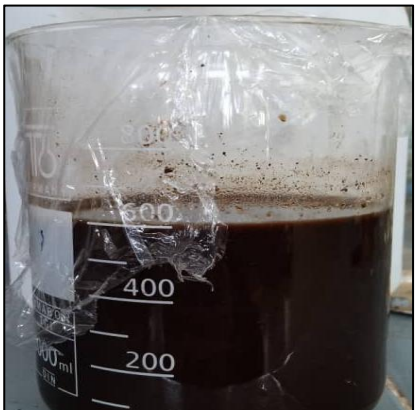




Figure 3.13: Fiber content procedures

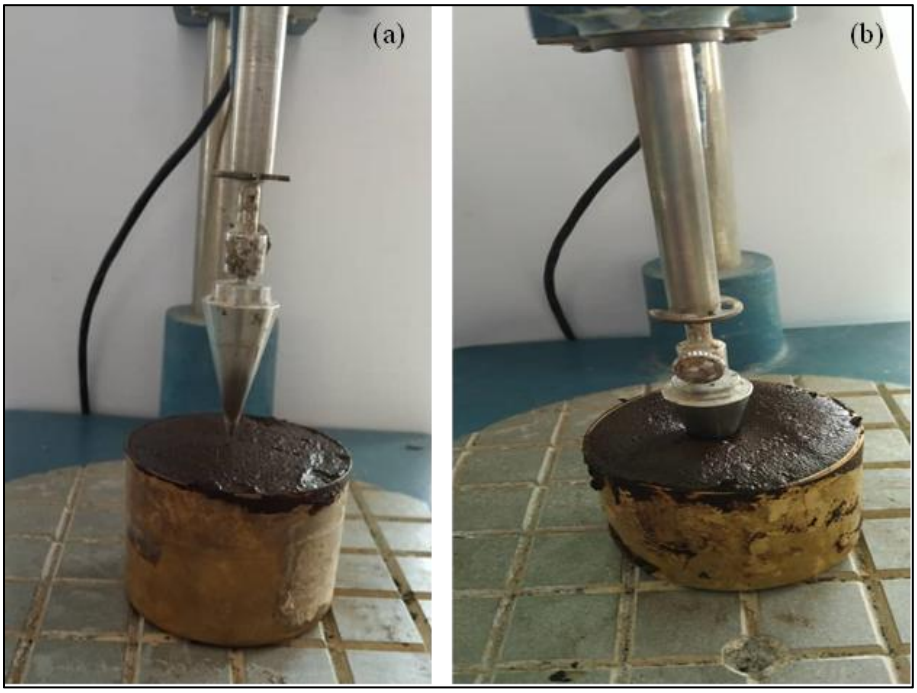
3.5.6 Atterberg Limit

The Atterberg limits, comprising of the liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) are fundamental parameters for characterizing the consistency and plasticity of fine-grained soils. These limits delineate the transitions between different states of soil consistency as moisture content varies from solid to semi-solid (SL), semi-solid to plastic (PL), and plastic to liquid (LL). The plasticity index (PI), defined as the numerical difference between LL and PL, quantifies the range of moisture content over which the soil exhibits plastic behaviour. However, due to the excessive moisture and organic matter, the plastic limit (PL) could not be reliably determined, and the plasticity index (PI) was inferred to be extremely high based on field behaviour and LL data.

3.5.6.1 Liquid Limit Determination

In this study, the cone penetrometer method was employed to determine the liquid limit of peat soil samples, following the procedure outlined in BS 1377: Part 2:1990, Clause 4.3. This method is preferred over the Casagrande apparatus due to its higher reproducibility and reduced operator dependency. Approximately 300 grams of air-dried peat soil passing through a 425 μm sieve were thoroughly mixed with distilled water to form a homogeneous paste. As shown in Figure 3.14, the prepared sample was placed into the cup of the cone penetrometer apparatus, ensuring a smooth surface without entrapped air. The standard stainless-steel cone, with a mass of 80 grams and an apex angle of 30 degrees, was positioned to just touch the soil surface. Upon release, the cone was allowed to penetrate the soil under its own weight for 5 seconds, and the depth of penetration was recorded. This procedure was repeated for soil samples at varying moisture contents to establish a relationship between moisture content and cone penetration depth. A graph was plotted with moisture content on the x-axis and corresponding penetration depth on the y-axis. The liquid limit was determined as the moisture content corresponding to a 20 mm penetration depth, as per the standard method.

The cone penetrometer apparatus was calibrated prior to testing using standard calibration procedures to ensure accuracy. Calibration involved verifying the mass of the cone and the timing mechanism to confirm the 5-second drop duration.



(a) Cone penetrometer apparatus (b) Sample testing in progress

Figure 3.14: Liquid Limit determination

3.5.6.2 Shrinkage Limit Determination

Linear shrinkage is a critical index test for evaluating the volumetric behaviour of fine-grained soils upon drying, particularly in organic soils such as peat. This test measures the reduction in length of a soil sample as it transitions from a saturated to a completely dry state, offering valuable insight into the soil's tendency to undergo desiccation cracking, structural degradation, and volumetric instability under drying conditions.

In this study, the linear shrinkage of the peat soil was determined following the procedure outlined in BS 1377: Part 2: 1990, Clause 6.5. The sample used for this test was taken from the batch corresponding to the 20 mm cone penetration reading during the liquid limit determination, ensuring the specimen had optimal workability and moisture content representative of its plastic state.

The selection of the sample at the 20 mm cone penetration depth for linear shrinkage testing is both methodologically sound and consistent with standard geotechnical practice. In accordance with BS 1377: Part 2: 1990, the liquid limit is defined as the water content at which a standard cone penetrates 20 mm into a soil paste in five seconds. This state represents the transition from plastic to liquid behaviour, indicating that the sample has achieved optimal workability and homogeneity. Using the soil at this specific moisture content ensures that the water distribution within the sample is uniform, minimizing measurement variability due to uneven drying or localized shrinkage. The sample exhibits maximum potential for volumetric deformation, making it ideal for assessing shrinkage behaviour under controlled drying conditions. Furthermore, the soil structure is in a remoulded, consistent condition, which improves repeatability of linear shrinkage measurements across different test batches.

To achieve measurement accuracy, the linear dimensions of the specimen specifically its final dried length (L_D) were measured using a calibrated digital vernier calliper with a resolution of 0.01 mm, ensuring high precision. The original mould length (L_O) was also verified using the same calliper before each batch of tests. The drying oven used to dehydrate the sample was regularly calibrated using a traceable digital thermometer, ensuring that all specimens experienced uniform thermal exposure (105 ± 5°C), which is critical for reliable shrinkage evaluation.

The use of the 20 mm penetration sample enhances the accuracy of the test results by eliminating inconsistencies that could arise from subjective moisture estimations or heterogeneous sample conditions. This approach aligns with recognized standards and ensures that the shrinkage results obtained are both representative and reproducible,

supporting the broader goal of accurately characterizing the soil's behaviour under drying conditions.

During the tests, a linear shrinkage mould was cleaned and lightly greased to avoid adherence and gradually filled with the soil sample. To minimize air entrapment, the soil was gently tapped into the mould using a non-metallic tamper. Excess soil was removed using a steel spatula to ensure the surface was flush with the top of the mould. Care was taken to remove any soil adhering to the edges of the mould.

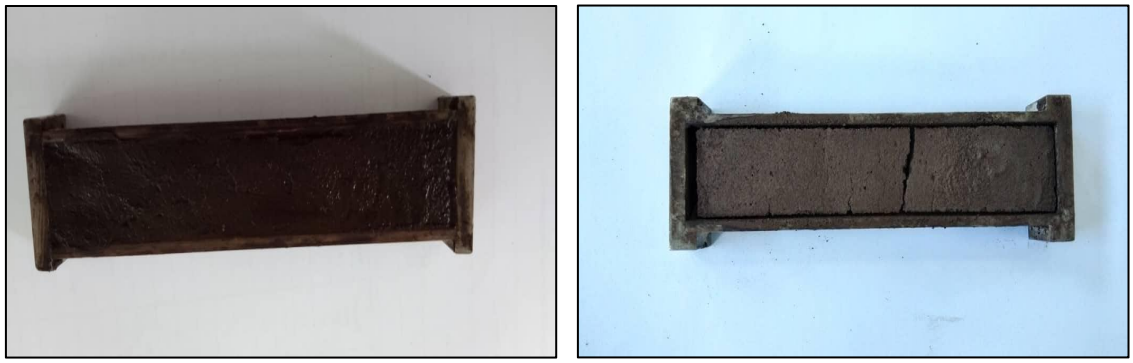
The filled mould was then placed in a ventilated drying oven set to a temperature of 105°C ± 5°C and left undisturbed for a minimum of 24 hours, or until a constant mass was observed. Oven calibration was verified monthly using a certified digital thermometer in accordance with laboratory quality standards. Upon drying, the sample was allowed to cool to room temperature before measurement. The final length of the dried specimen (L_D) was measured using a digital vernier calliper (accuracy ±0.01 mm), and the original mould length (L_O) was recorded. The percentage of linear shrinkage was calculated using the following formula:

$$\text{Linear shrinkage (\%)} = \left(1 - \frac{L_D}{L_0}\right) \times 100 \qquad \text{Equation 3.6}$$

Where,

L_D = length of the oven dry specimen (mm)
L_O = original length of the specimen (mm)

Visual documentation of the shrinkage process was recorded, with Figure 3.15(a) showing the sample prior to drying and Figure 3.15(b) illustrating the final length after cooling.



(a) Before Oven-Dried (b) After Oven-Dried

Figure 3.15: Sample for Linear Shrinkage Determination

3.5.7 Compaction by Standard Proctor test

Soil compaction is defined as the mechanical process of increasing the dry density of a soil by reducing the volume of air voids through the application of external energy under controlled moisture conditions. In geotechnical engineering, compaction enhances the shear strength, stiffness, and bearing capacity of soils while reducing settlement and permeability, making it a widely adopted technique in ground improvement and stabilization projects. In this study, the Standard Proctor compaction test was conducted to determine the maximum dry density (MDD) and optimum moisture content (OMC) of both untreated and treated peat soil samples. The procedure adhered strictly to the methodology outlined in BS 1377: Part 4: 1990, Clause 3.3, which is the standard for light compaction testing.

The test involved mixing oven-dried peat soil with varying amounts of distilled water to achieve pre-determined moisture contents. The moistened soil was compacted into a cylindrical mould in three equal layers; each layer being compacted by 27 blows from a 2.5 kg rammer dropped from a height of 300 mm. The compaction apparatus was calibrated prior to testing using certified gauges and calibration blocks, and the weighing balance used for sample preparation was calibrated weekly with traceable standard weights.

After compaction, the bulk and dry densities of the compacted specimens were calculated. The dry density (ρ_a) was computed using the following formula:

$$\rho_d = \frac{\rho_w}{\frac{w}{100} + \frac{1}{G_s}} \quad \text{Equation 3.7}$$

Where:

ρ_d = dry density of soil (g/cm^3)
ρ_w= density of water (g/cm^3)
G_s= specific gravity of the soil that being tested

A series of tests were conducted with different moisture contents to develop the compaction curve, where dry density was plotted against moisture content. The peak of this curve corresponds to the OMC, the moisture content at which the soil achieves its maximum dry density under the applied compactive effort. This test was repeated for peat samples treated with varying percentages of stabilizing additives (SH-85, rubber crumb and rubber powder) to evaluate the influence of additives on compaction behaviour. The comparative analysis allowed for identifying the most effective additive dosage based on shifts in the MDD and OMC values.

The Standard Proctor test provides a reliable and standardized approach to evaluating compaction characteristics under known energy input, making it suitable for field replication. However, for highly organic and compressible soils like peat, the light compaction energy may not fully simulate field conditions, and the fibrous content can introduce variability. To mitigate this, samples were homogenized thoroughly, and triplicate tests were conducted for each moisture level to improve result reliability. Hence,

the optimum moisture content (OMC) and maximum dry density (MDD) were computed and tabulated based on the laboratory experiments, and the results were reported.

3.6 Mechanical Testing for Soil Strength

To evaluate the mechanical behaviour and reinforcement efficacy of the peat soil used in this study, two principal tests were employed: the Unconfined Compression Strength (UCS) test and the California Bearing Ratio (CBR) test. These tests are critical in quantifying the strength performance of both untreated and stabilized peat samples under controlled laboratory conditions. Each test is discussed in detail in the following subsections.

3.6.1 Unconfined Compression Strength (UCS) test

The Unconfined Compression Strength (UCS) test is a widely used method for evaluating the undrained shear strength of cohesive soils, particularly when confining pressure is absent. In this study, the UCS test was conducted in accordance with BS 1377: Part 7: 1990, Clause 4, which outlines the procedures for testing cylindrical soil specimens under axial loading conditions without lateral confinement.

Soil specimens were prepared according to pre-designed mix compositions and compacted in three layers using a standard compaction tool. The compaction mould was fabricated to a custom internal diameter of 38 mm and height of 76 mm, as specifically designed by the author to suit peat's low strength and fibrous structure. To compact the stabilized peat specimens, a hand-held compaction tool was used to compact the sample in three equal layers within the 76 mm tall cylindrical mould. Each layer, approximately 25 mm thick, was compacted with 10 uniform blows to ensure consistent compactive effort across specimens while avoiding over compaction that could disrupt the internal structure

of the stabilized mixture. The compaction tool was designed with a flat base, slightly smaller than the internal diameter of the mould to prevent binding and was placed in direct contact with the surface of each soil layer prior to compaction. This gap-free contact ensured even distribution of force across the specimen. During dynamic compaction, the tool was lifted only a short distance (approximately 100–200 mm) to avoid excessive impact energy or rebound, which could affect layer integrity. A dead load was applied while the tool was already seated on the soil surface, promoting uniform density without disturbing the stabilized structure. After compaction, samples were extruded using a mechanical extractor, and the height and mass of each specimen were measured to verify uniformity and ensure that the target density was consistently achieved across all samples.

Then, the extruded samples were individually wrapped in plastic film to preserve moisture and were cured under air-drying conditions at room temperature (approximately 27 ± 2°C) for periods of 7, 28, and 56 days. The air curing method was intentionally chosen to simulate gradual field desiccation while avoiding full saturation, which could induce premature softening in organic soils. No submerging or additional water conditioning was applied throughout the curing process. The curing duration was selected to monitor progressive strength development over time and assess the durability of the stabilizing agents under dry conditions. Each cured specimen was placed on the platen of the fully automated digital unconfined compression machine (Model UTEST/UTM 0108), and axial load was applied at a constant strain rate of 1.00 mm/min, as specified in BS 1377-7. Load and deformation readings were recorded automatically until sample failure occurred. The test setup is illustrated in Figure 3.16, while Figures 3.17 to 3.19 detail the custom cylindrical mould and preparation stages. The UCS machine was calibrated

monthly using a certified load cell and displacement transducer. The calibration ensured measurement precision within ±1% for load and ±0.01 mm for displacement.

A total of 324 samples were prepared for UCS testing, covering all combinations of treatment levels and curing durations. Each test was performed in triplicate to ensure statistical reliability. The examples of UCS sample before and after test were shown in Figure 3.20. The average UCS values were recorded and used to assess the effect of additive type and curing time on strength performance. The UCS test is chosen because it is simple, cost-effective, and well-suited for rapid evaluation of cohesive soils like peat, especially in the early phases of stabilization. However, for highly fibrous peat, achieving uniform compaction and specimen homogeneity can be challenging. Furthermore, the absence of lateral confinement may not fully represent in-situ stress conditions. These limitations were mitigated through consistent sample preparation protocols and custom mould fabrication. The results obtained from the UCS testing are essential in establishing the optimum binder content and in understanding the strength gain behaviour of stabilized peat over time. These insights directly inform the design and application of soil improvement strategies in organic environments.



Figure 3.16: Unconfined Compression Strength (UCS) Test Apparatus



Figure 3.17: Unconfined Compression Strength (UCS) Test Mould

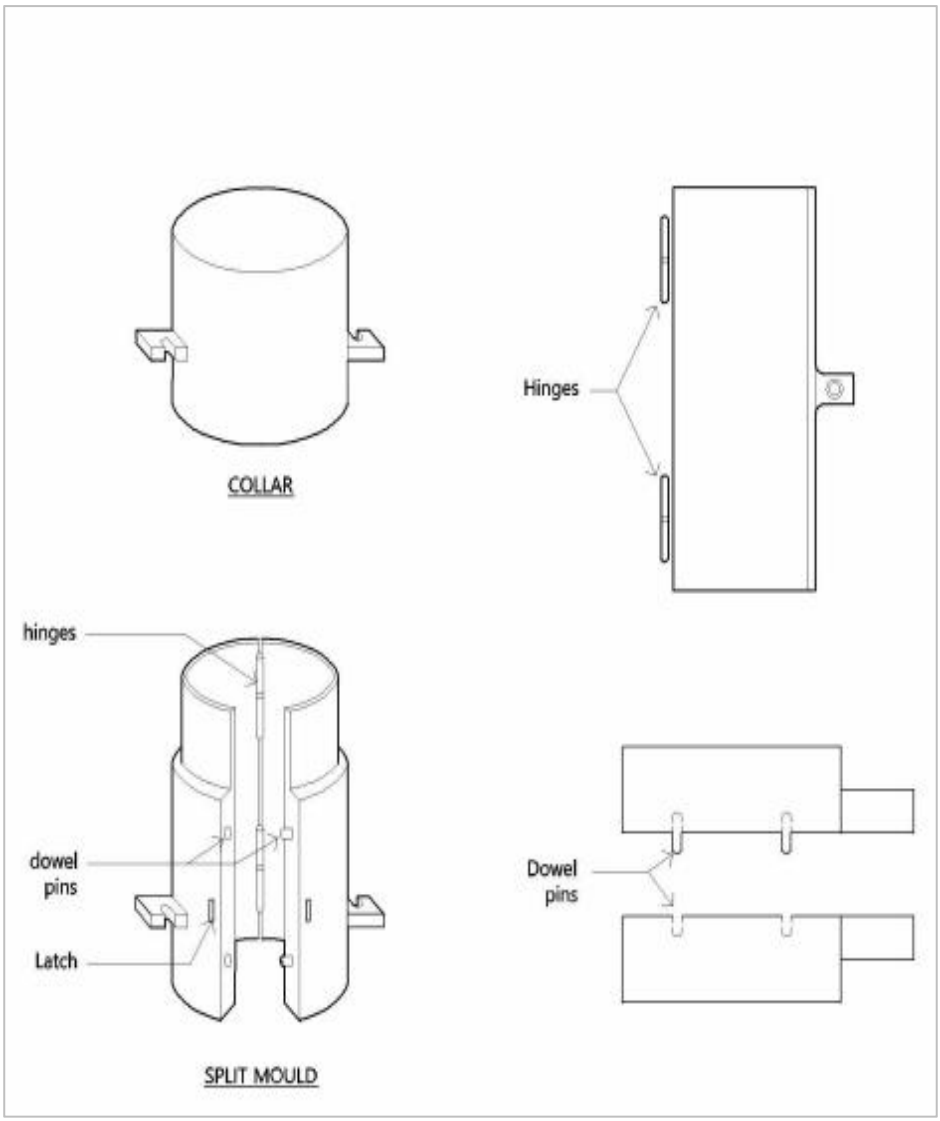


Figure 3.18: Unconfined Compression Strength (UCS) Test Mould Design

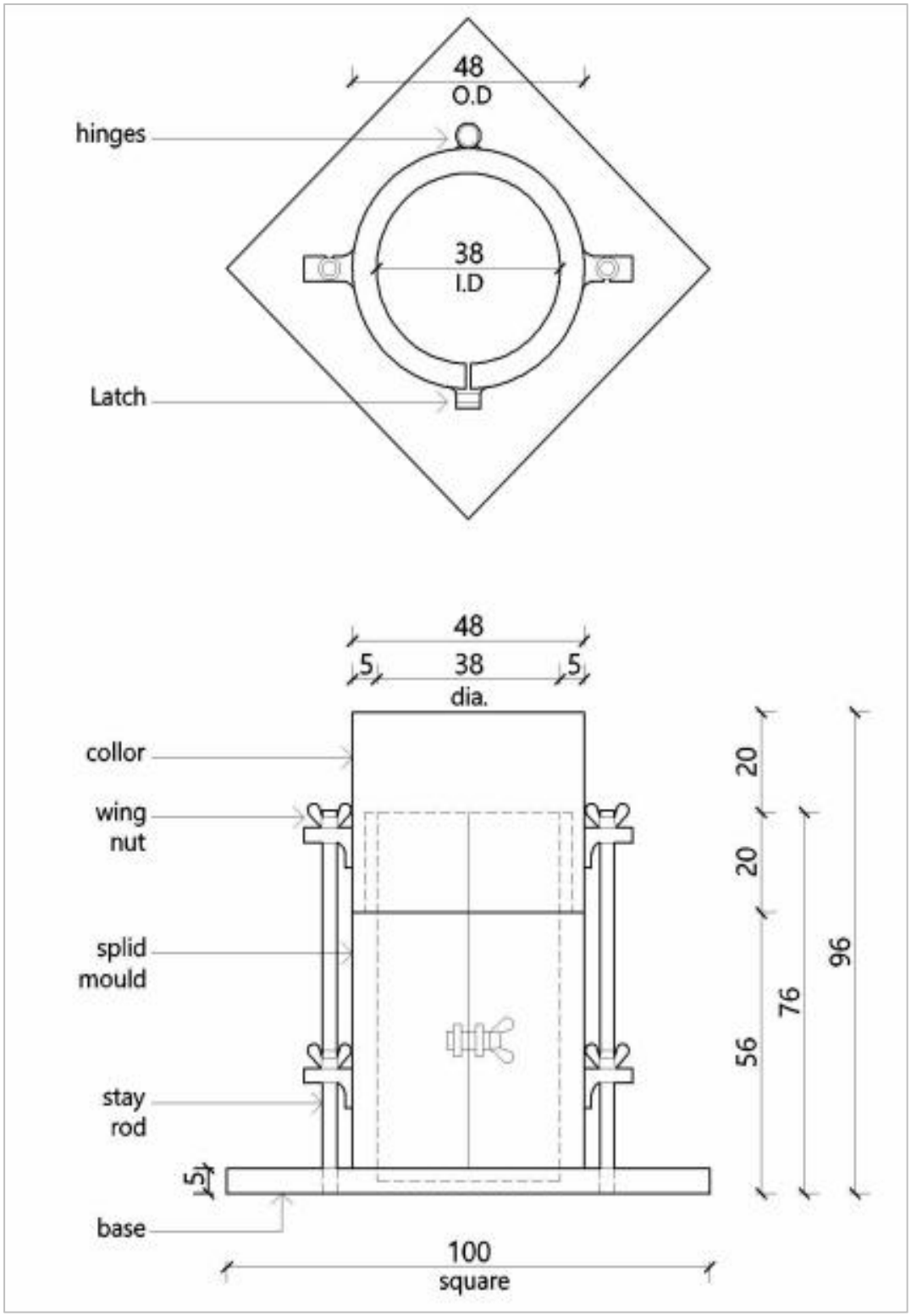


Figure 3.19: Unconfined Compression Strength (UCS) Test Mould Design (detailed)

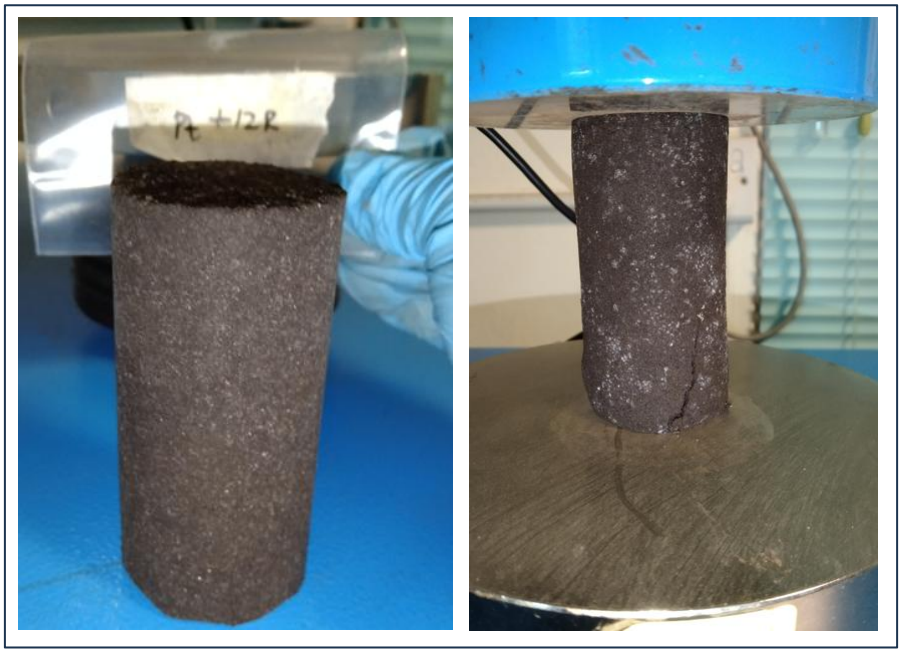


Figure 3.20: UCS samples before and after tested

3.6.2 Liquid Limit and Shrinkage Limit of Untreated and Treated Peat

This study determines the liquid limit and shrinkage limit through the Atterberg's Limit test for peat. The plastic limit of peat is not attainable since rolling peat to a thread-like shape is difficult due to the pasty texture of peat. A cone penetration test was performed to determine the liquid limit of the peat, which was the point at which the peat began to change states from plastic to liquid. Figure 3.21 and Figure 3.22 depicts the water content as corresponding to 20 mm cone penetration for natural and dry peat. The liquid limit for natural state shows very high moisture contents with 433.5% which is thrice as high as the liquid limit of the dry state of 114.4%. Peat with an exceptionally high liquid limit indicates its poor engineering characteristics and high compressibility. The liquid

limit of the peat is substantially decreased to 114.4% by the process of drying, however, it remains high in compressibility.

Figure 3.23 illustrated the result of liquid limit and shrinkage limit for peat soil and peat stabilized with waste rubber (rubber crumb and rubber powder) and SH-85. Figure 3.23 shows the effect of different stabilization mixtures on the liquid limit (LL) and shrinkage limit (SL) of peat soil with various percentages of rubber waste and SH-85. The addition of SH-85 into the mixture results in a gradual decrease in the liquid limit as the dosage increases. A sharp reduction in LL is evident from natural peat (433.5%) to treated samples that is mostly below 100%. Notably, the liquid limit decreases significantly after stabilization, particularly with SH-85 and combined treatments. This drop implies a reduction in the soil's plasticity and water-holding capacity, which is critical in improving constructability and reducing post-construction settlement (Duraisamy et al., 2007).

Nevertheless, the decrease appears to plateau at a liquid limit ranging from 97% to 99%, except when 12% SH-85 is added, which causes a rapid drop to 48.4%. The inclusion of RC in the samples results in a substantial decrease in liquid limits, ranging from 28% to 85%. This combination greatly improved the characteristics of the peat. Furthermore, the inclusion of RP in peat results in a decrease in the liquid limit. The results indicate significant improvements, although not as effective as the addition of rubber crumbs. This finding aligns with previous research, such as (Kazemian et al., 2011b), which demonstrated that stabilizing agents significantly reduce peat moisture sensitivity and improve penetration resistance, owing to better interparticle bonding and matrix densification. The results are also agree with previous findings by (B. B. K. Huat et al.,

2005), who reported that chemical stabilizers such as silica-based agents reduce liquid limits and improve strength characteristics of tropical peat.

Conversely, the shrinkage limit remains consistently low across samples, mostly below 5%, with only minor increases in a few mixtures. Figure 3.23 indicates the shrinkage value of peat is 2.81% in its dry condition and 29.86% in its natural state. Untreated peat exhibits significant shrinkage because it retains a large amount of water, suggesting that it is highly susceptible to desiccation cracking. The shrinkage limit of peat treated with different percentages of SH-85 stabiliser, which ranges from 1.54 to 2.91, is marginally but not significantly reduced. The shrinkage limits of samples containing rubber crumbs in this study range from 0.94 to 3.95. Hence, the inclusion of 5% rubber crumbs falls within the acceptable limits for construction purposes, whereas a larger dose exhibits excessive enhancement that may result in expansion problems. This indicates a suitable quantity of rubber to be used. Nevertheless, the addition of rubber powder is causing a reduction values in some of the samples containing rubber powder, ranging from 2.03 to 1.03. This range is probably optimum for minimizing issues related to cracking and shrinking.

The relatively stable and low SL values, despite reductions in LL suggest that while water affinity is reduced, residual plasticity persists. This phenomenon supports the argument that stabilizers like SH-85 reduce free water but may not fully alter the inherent fibrous structure of sapric peat. The persistent low shrinkage limit observed also supports the argument by Mohd Razali et al., (2019), who noted that even treated peat may exhibit residual deformation behaviour, especially under fluctuating moisture conditions, due to its organic matrix. Furthermore, Moulton (1980) indicated that the suggested criteria for

subgrade soil required a shrinkage limit of less than 6%. Das & Sobhan (2018) agreed with the statement that a shrinkage limit of less than 3% is commonly used as an indicator to determine if soils are suitable for use in earthworks that involve compacted fills and subgrades, highlighting the need for combined mechanical and chemical interventions.

In conclusion, the shrinkage limit of untreated peat is extremely high. The application of SH-85 does not significantly enhance the reduction of peat shrinkage. However, the use of rubber crumbs and rubber powder in the optimum amounts of 5-15% can effectively decrease the shrinkage limit of peat to the values that acceptable for construction purposes. Still, an excessive amount of addition could potentially create significant issues. Hence, it is vital to identify and confirm the optimum percentage of mixtures, since subgrade with lower shrinkage limits is typically preferred for providing durable and less moisture-sensitive subgrade performance.

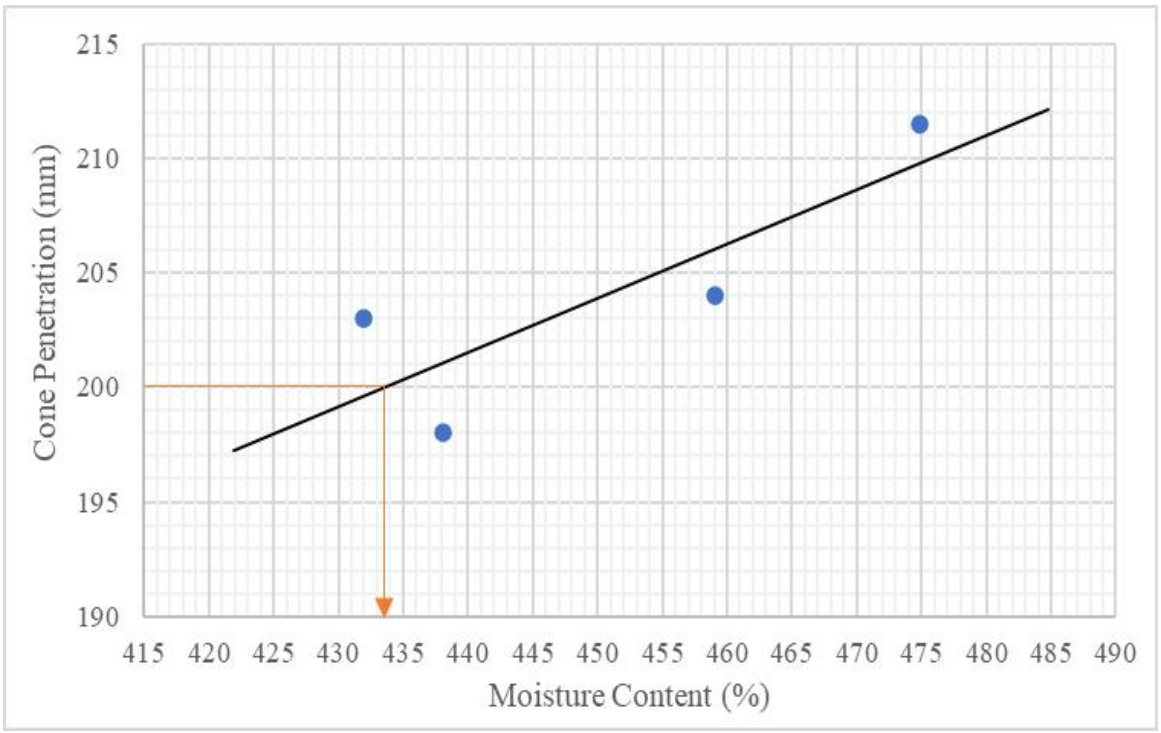


Figure 3.21: Liquid limit determination for natural peat

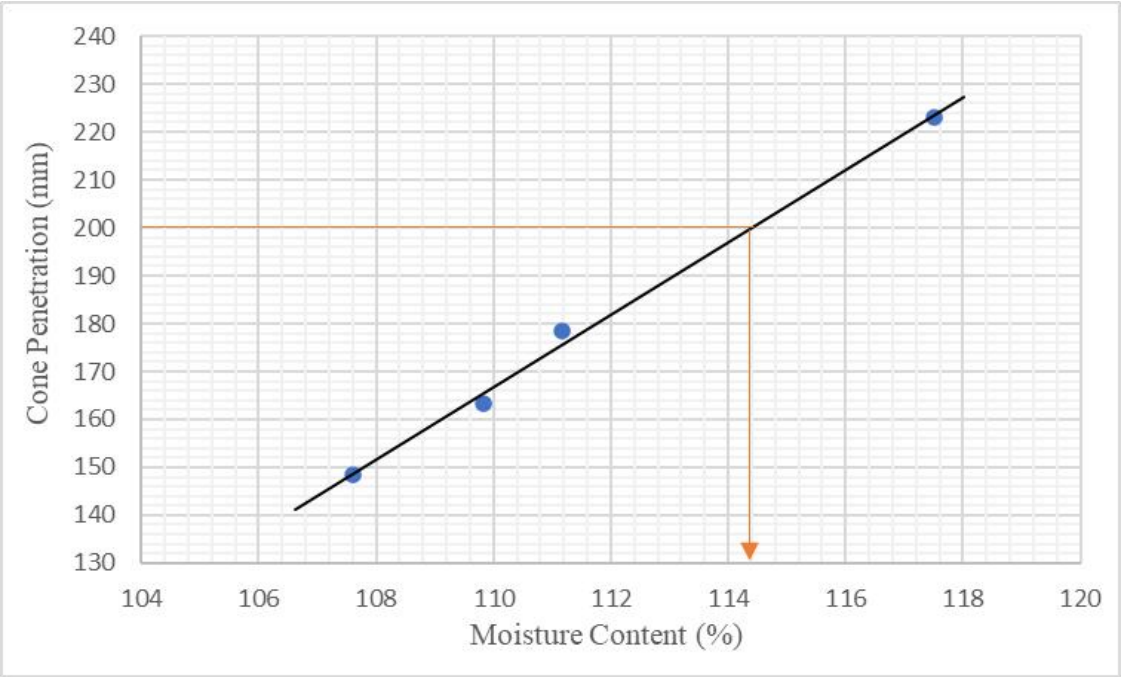


Figure 3.22: Liquid limit determination for dry peat

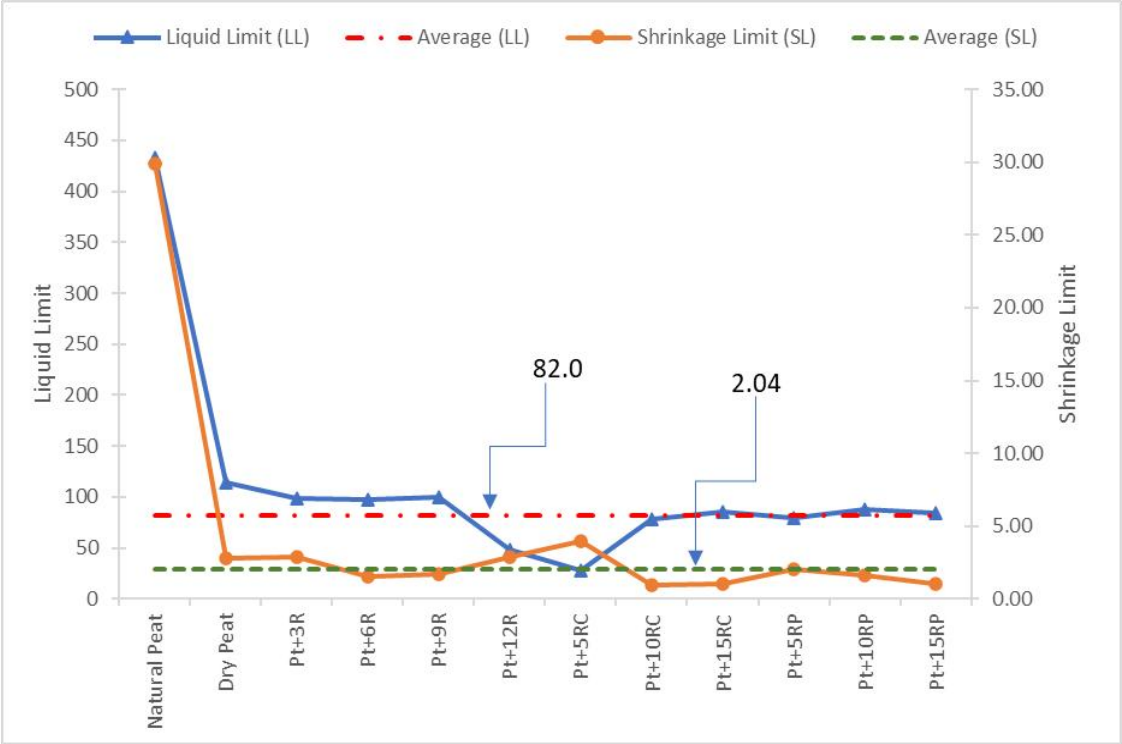


Figure 3.23: Result of liquid limit and shrinkage limit on different percentage of rubber waste and SH-85 of stabilized peat soil.

3.6.3 California Bearing Ratio (CBR) test

The California Bearing Ratio (CBR) test is an empirical penetration test designed to evaluate the load-bearing capacity of subgrade soils, sub-bases, and base courses used in pavement construction. The CBR value, expressed as a percentage, reflects the ratio of the force required to achieve a certain penetration in the test soil to that required in a standard crushed stone. Higher CBR values indicate greater soil strength and reduced deformability under loading (Das & Sobhan, 2018).

In this study, the CBR test was conducted following the guidelines provided in BS 1377: Part 4: 1990, Clause 7. The primary objective was to assess the strength enhancement of untreated and stabilized peat samples by measuring their resistance to penetration under unsoaked conditions. Soaked tests were not conducted due to the temporary unavailability of the necessary equipment. As a result of the constraints associated with conducting experiments in soaked conditions, the testing was solely carried out in unsoaked conditions.

Soil specimens were prepared by mixing peat with various stabilizing additives in controlled proportions. The blended material was compacted in a standard CBR mould (internal diameter: 152 mm, height: 178 mm) in five equal layers. Each layer received 62 evenly distributed blows using a 50 mm diameter, 2.5 kg metal rammer dropped from a height of 300 mm, conforming to the energy requirements of the Standard Proctor compaction method. Post-compaction, the collar of the mould was removed, and excess

soil was trimmed using a steel straightedge to create a uniform, level surface. The entire mould and sample were weighed and subsequently allowed to cure under ambient laboratory conditions (27 ± 2°C) for 7 and 28 days. The curing method employed was air curing, which allowed moisture to dissipate gradually, improving sample stability and replicating field desiccation conditions. After curing, the specimen was placed in the fully automated digital CBR testing machine (Model: UTEST UTC-0860), where a 50 mm diameter cylindrical plunger was vertically penetrated the soil surface at a standard rate of 1.25 mm/min, using a motorized load frame. The applied force and corresponding penetration were recorded continuously using calibrated load and displacement sensors. The test apparatus was calibrated monthly using certified proving rings and digital displacement gauges, compliant with ASTM D1883 laboratory standards, ensuring load measurement precision within ±1% and displacement accuracy of ±0.01 mm. The California Bearing Ratio (CBR) value was calculated based on the measured force per unit area required to achieve standard penetration depths of 2.5 mm and 5.0 mm. These values were automatically recorded and graphically represented by the computer-integrated data acquisition system connected to the CBR testing apparatus as shown in Figure 3.24.

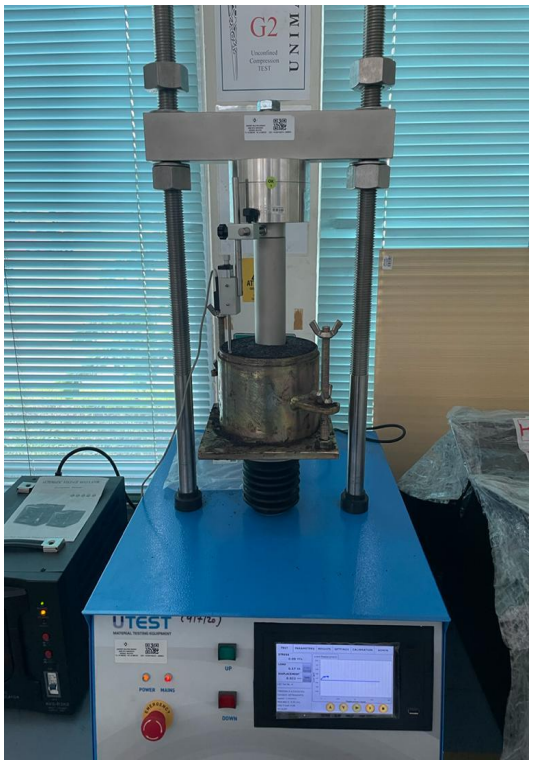


Figure 3.24: California Bearing Ratio (CBR) Test Apparatus

3.7 Scanning Electron Microscopy (SEM)

The mechanical performance of reinforced peat soil, as determined through UCS and CBR tests, reflects macroscopic improvements resulting from the addition of stabilizing agents. However, to fully understand the mechanisms behind these enhancements, it is essential to examine the microstructural and elemental changes occurring within the soil matrix. Therefore, detailed morphological and compositional analyses were conducted to complement and explain the mechanical behaviour observed in Objective 1.

Scanning Electron Microscopy (SEM) is a high-resolution imaging technique used to examine the surface morphology, particle bonding, and microstructural features of solid materials at the microscale. In this study, SEM analysis was conducted to investigate the microstructural characteristics of peat soil samples treated with various proportions of stabilizing additives. The objective was to assess the interaction between the soil matrix and additives at a microscopic level and to correlate morphological changes with mechanical performance improvements observed in previous tests. To ensure optimal imaging and accuracy, specimen preparation adhered to standard protocols for SEM

analysis of non-conductive materials (Goldstein et al., 2017). Treated peat samples were carefully remoulded and air-dried, then crushed into small, representative fragments. These fragments were mounted onto non-conductive carbon adhesive tape placed on aluminum SEM stubs to ensure stability during scanning.

To further support the microstructural observations, Energy Dispersive X-ray Spectroscopy (EDX) was employed alongside SEM to identify and quantify the elemental composition of the treated samples. EDX analysis enables the detection of chemical elements within specific microstructural regions, providing insight into the distribution and bonding behaviour of additives within the peat matrix. This compositional information is essential for understanding the chemical mechanisms contributing to the observed mechanical improvements in UCS and CBR tests. Scanning Electron Microscopy (SEM) is a high-resolution imaging technique used to examine the surface morphology, particle bonding, and microstructural features of solid materials at the microscale. In this study, SEM analysis was conducted to investigate the microstructural characteristics of peat soil samples treated with various proportions of stabilizing additives. The objective was to assess the interaction between the soil matrix and additives at a microscopic level and to correlate morphological changes with mechanical performance improvements observed in previous tests.

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Due to the organic and insulating nature of peat, the samples were coated with a thin conductive layer to enhance image clarity and electron interaction. A magnetron sputter coater was used to deposit a platinum (Pt) film approximately 10 nm thick over the sample surface. The sputtering process was carried out in a vacuum chamber for 15 minutes, ensuring uniform coating and minimizing surface charging during SEM operation. SEM imaging was performed using a Hitachi TM4000Plus Scanning Electron Microscope, which utilizes a thermionic tungsten filament as the electron source. The electron beam was accelerated at 20 kV, and the microscope operated in low vacuum mode to accommodate the porous and moisture-sensitive characteristics of peat. Imaging was conducted at magnifications ranging from 1,000× to 5,000× to capture fine morphological details such as pore structure, additive dispersion, and fiber-soil bonding.

The SEM unit was calibrated prior to imaging using a traceable gold-on-carbon resolution standard in accordance with the manufacturer's guidelines and laboratory quality assurance procedures. This ensured consistent image resolution and dimensional accuracy. The electron beam scans the sample's surface in a raster pattern, and the resulting interactions generate secondary and backscattered electrons, which are collected by detectors to form the image. The backscattered electron mode was used to differentiate between organic soil matter and denser mineral phases or additives, while the secondary electron mode provided topographical contrast. Figure 3.25 illustrates the SEM equipment used in this study for capturing microstructural details of the stabilized peat samples.

To further support the microstructural observations obtained from SEM analysis, Energy Dispersive X-ray Spectroscopy (EDX) was utilized to identify and quantify the elemental composition of the reinforced peat samples. EDX is an analytical technique that

detects characteristic X-rays emitted from a specimen when bombarded with a focused electron beam. These X-rays are unique to each element, allowing for precise qualitative and semi-quantitative identification of the elements present in the sample. When combined with SEM imaging, EDX provides spatially resolved elemental analysis, making it a powerful tool for understanding the chemical interactions at the microstructural level.



Figure 3.25: Scanning Electron Microscopy (SEM) Apparatus

In this study, EDX analysis was conducted on selected regions of the treated peat samples to examine the presence and distribution of stabilizing elements introduced through additives. The primary goal was to detect elements such as calcium (Ca), silicon (Si), aluminum (Al), and other potential constituents associated with the stabilizers used. By comparing the elemental composition of treated and untreated peat, the analysis offers insights into the chemical bonding mechanisms, such as pozzolanic reactions, that may contribute to strength development and improved bearing capacity.

Additionally, the EDX spectrum and corresponding elemental maps enabled the identification of reaction products and the degree of homogeneity in additive dispersion throughout the soil matrix. This information is crucial in validating the effectiveness of the stabilization treatment and in correlating specific chemical features with the mechanical performance enhancements observed in UCS and CBR tests. The integration of EDX results with SEM observations thus provides a comprehensive understanding of the physicochemical changes underpinning peat soil stabilization.

The SEM and EDX tests were conducted as it provides detailed insights into the physical bonding, porosity, and particle interaction at the microscale, which cannot be captured by conventional mechanical tests. However, sample dehydration and coating may alter organic structures slightly, and non-uniform surfaces may limit the consistency of imaging. These were mitigated by selecting flat, representative fragments and ensuring consistent coating thickness. Figure 3.26 illustrates the process of EDX analysis used in this study for capturing microstructural details of the stabilized peat samples.

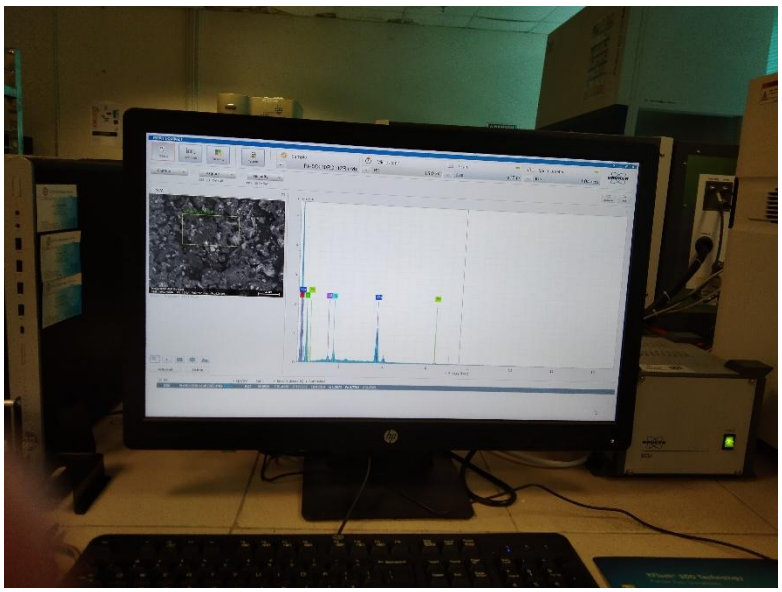


Figure 3.26: Energy Dispersive X-ray Spectroscopy (EDX) in progress

3.8 Modelling of the Reinforced Soil by GeoStudio (2022)

The rapid advancement in computing capabilities has led to the development of powerful numerical software tools for engineering and scientific analyses. These tools, once confined to academic research, are now widely accessible and form a fundamental part of practical engineering design. Among these, finite element analysis (FEA) software has become a critical component in geotechnical and structural engineering, enabling detailed simulation of complex physical behaviours and improving the accuracy of predictive models (Potts et al., 2001).

In this study, SIGMA/W and SLOPE/W, sub-programs of the GeoStudio® software suite developed by Geo-Slope International, were employed to model the deformation and stability behaviour of reinforced peat soil under embankment loading conditions. These tools allow for comprehensive simulation and performance evaluation of soil-structure systems under various boundary and loading conditions.

3.8.1 Stress-Deformation Analysis with SIGMA/W

SIGMA/W is a two-dimensional finite element analysis tool designed to evaluate the stress and deformation characteristics of earth structures, such as embankments, foundations, and retaining walls. It supports both linear elastic and nonlinear elastic-plastic effective stress models, offering flexibility in simulating the mechanical response of soils under varied environmental and loading scenarios (GeoStudio, 2022). SIGMA/W was utilized to simulate the settlement and horizontal displacement of highway embankments constructed on reinforced peat soil. The material input parameters such as Young's

modulus, Poisson's ratio, cohesion, angle of internal friction, and permeability on both untreated and stabilized samples were derived from laboratory tests or from the established literatures. The model incorporated incremental loading, simulating traffic and fill loads, while accounting for undrained and partially drained conditions typical of peat deposits. Calibration of the SIGMA/W model was achieved through comparison with benchmark data and literature case studies to validate the predictive accuracy of the simulation. The model's reliability was further enhanced by implementing convergence checks, mesh sensitivity analysis, and applying appropriate boundary conditions.

3.8.2 Slope Stability Analysis with SLOPE/W

To assess embankment stability, SLOPE/W was employed for limit equilibrium analysis. This tool calculates the Factor of Safety (FoS) against shear failure along critical slip surfaces, which are generated and analyzed using methods such as Bishop's Simplified, Janbu, and Morgenstern-Price techniques. The analysis integrates pore-water pressure distributions derived from either measured field data or numerical simulations in SIGMA/W. In the present study, SLOPE/W was applied to embankment profiles reinforced with stabilized peat to quantify the improvement in stability due to the inclusion of additives. Stability analyses were conducted for both short-term (undrained) and long-term (drained) conditions. The outputs provided insight into potential failure modes and helped to optimize the geometry and material design of embankments constructed on weak organic soils.

The use of SIGMA/W and SLOPE/W in this study enables the simulation of real-world geotechnical behaviour, offering a cost-effective and efficient means to predict performance and assess risk under multiple scenarios. However, model accuracy depends

heavily on the quality of input data and assumptions made regarding boundary conditions and soil behaviour, necessitating rigorous validation and sensitivity analysis. The numerical models developed in this study incorporated the optimum mix designs determined from laboratory testing of UCS and CBR, enabling a holistic assessment of the reinforced soil's field performance. The simulations allowed for cross-validation of laboratory results, supported engineering judgment, and informed the design recommendations for road embankments on peat.

3.9 Design Methodology and Scientific Framework for Numerical Modelling using GeoStudio

This section outlines the design methodology adopted in this research, derived directly from empirical and experimental findings as presented in preceding chapters. The methodology presented here contributes to academic research by translating optimized laboratory-based stabilization parameters into a validated finite element simulation, thereby addressing a significant knowledge gap in the mechanistic behaviour of stabilized tropical peat.

The numerical analysis was conducted using GeoStudio 2022, specifically employing SIGMA/W for deformation and consolidation analysis and SLOPE/W for evaluating stability. The design follows a scientifically structured procedure, underpinned by the Modified Cam Clay (MCC) model calibrated for stabilized sapric peat from Kg Endap, Sarawak. The use of these tools and methods is validated by their widespread application in scholarly literature for advanced modelling of highly compressible and organic soils (Karami et al., 2023).

3.9.1 Step-by-Step Scientific Procedure for FEM-Based Design Using GeoStudio

i. **Step 1: Define Initial Geometry**

A 2D plane strain cross-section was established to simulate embankment construction. Stratigraphic profiles were generated based on distinct regions representing different kinds of soil. Soil regions were delineated to represent peat, clay, and embankment materials using the laboratory-characterized soil layers.

ii. **Step 2: Initial Pore Water Pressure Definition**

Initial pore water pressure (PWP) conditions were established based on a water table located 1 m below ground level. This condition was defined via a phreatic surface through a series of connected nodes, as per recommendations in Geo-Slope International (2019).

iii. **Step 3: Transient Time-Stepping Configuration**

Time-dependent behaviour was modelled using a transient analysis with a total duration of 7 days, segmented into seven steps, to reflect the consolidation and staged embankment loading processes.

iv. **Step 4: Embankment Construction Simulation**

The embankment was modelled in five stages: an initial in-situ condition followed by four sequential 0.5-meter lifts. SIGMA/W's parent-child analysis structure was utilized to simulate progressive construction, where each lift analysis inherits stress and pore pressure conditions from its predecessor.

v. **Step 5: Define Soil Constitutive Parameters**

Constitutive models (Mohr-Coulomb and MCC) were calibrated using parameters

obtained from laboratory testing of the optimal stabilized mix (5% cement + 15% RC + 6% SH-85). Key parameters included:

a. Initial void ratio (e)

b. Saturated unit weight (γ_{sat})

c. Compression index (λ) and swelling index (κ)

d. Poisson's ratio (ν)

e. Effective friction angle (φ')

These parameters were chosen to reflect actual site-specific behaviours and were validated against regional literature as shown in Table 5.1.

vi. **Step 6: Material Assignment and Region Delineation**

Individual soil regions were created and meshed to simulate real-world boundaries. Material properties, including hydraulic conductivity and volumetric water content functions, were assigned based on verified sources.

vii. **Step 7: Boundary Conditions and Mesh Generation**

Boundary conditions were applied with fixed displacements at the model base and lateral constraints along vertical boundaries. A global element size of 1 m was specified, with local mesh refinement in high-stress regions.

viii. **Step 8: Model Execution and Result Evaluation**

The model was run to visualize deformations, pore pressure distributions, and vertical displacements. Outputs were analysed at Gauss integration points and

nodes of interest. Graphical outputs validated the stress-strain response of the stabilized peat.

ix. **Step 9: Stability Analysis using SLOPE/W**

The factor of safety (FoS) was computed using SLOPE/W, with the stress field imported from SIGMA/W. The Morgenstern-Price method was adopted, which is suitable for complex, non-circular slip surfaces in organic soils.

x. **Step 10: Pavement Surcharge Simulation**

A 10 kPa surcharge was applied to the embankment crest to simulate low-volume traffic load. This was included in the SLOPE/W analysis to assess post-construction slope stability.

xi. **Step 11: Optimization and Sensitivity Review**

Critical slip surfaces were identified and reviewed. The model was reanalysed with modified parameters to assess sensitivity and optimize the design.

This multi-step procedure enables scientifically grounded predictions of settlement and stability in embankment projects on stabilized peat. Unlike generic engineering workflows, the approach presented here is a product of calibrated modelling based on verified laboratory findings, site-specific conditions, and parametric optimization to ensuring strong research contribution. The Sequence of finite element design using GeoStudio 2022 is shown in Figure 3.27.

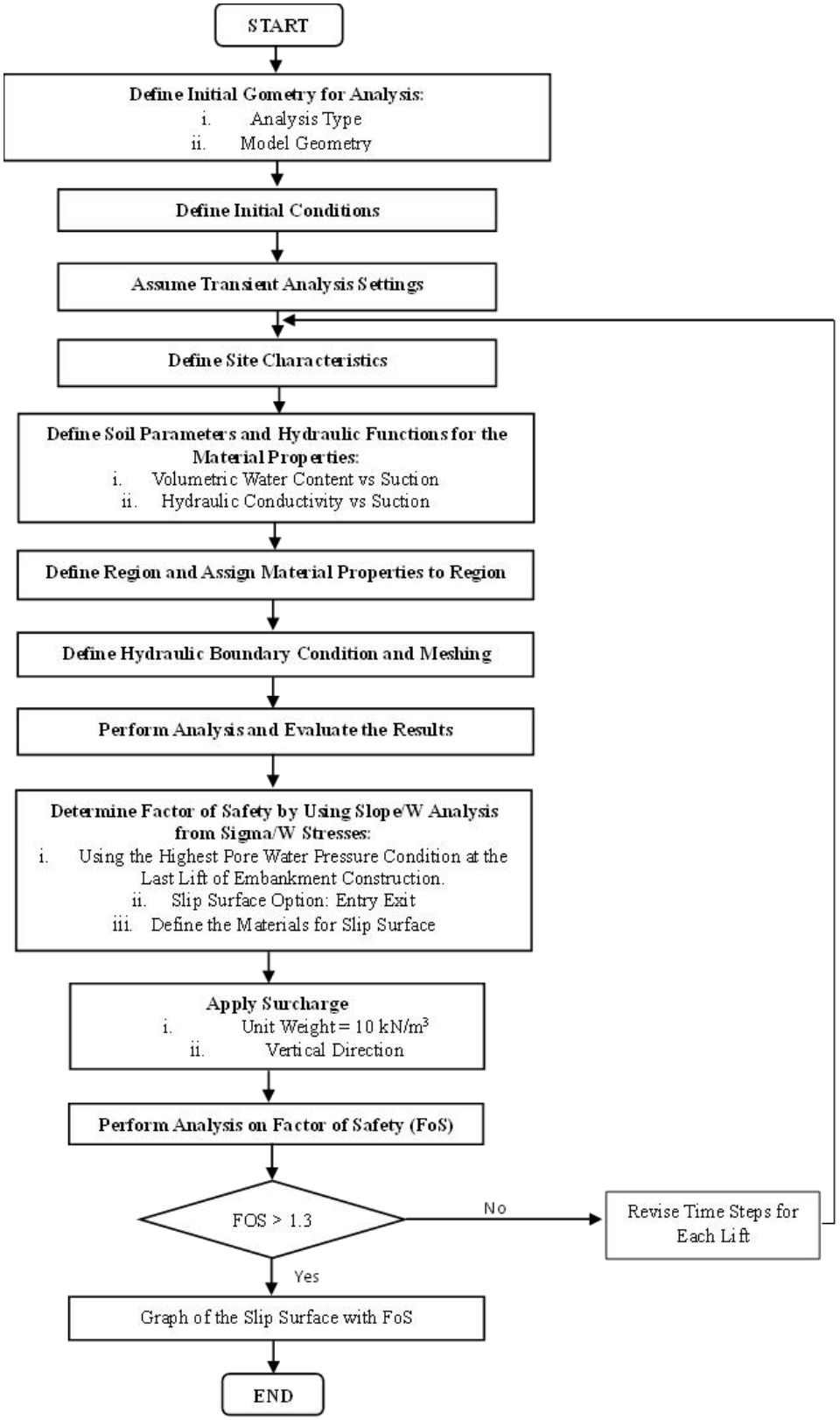


Figure 3.27: Sequence of finite element design using GeoStudio 2022

3.10 Summary

This chapter detailed the integrated methodology comprising laboratory testing, microstructural analysis, experimental procedures, test setups, parameters, and analytical approaches employed to evaluate the behaviour of reinforced peat soil for subgrade stabilization. The methodology was developed with a focus on ensuring scientific rigor, traceability, and reproducibility in accordance with international standards such as BS 1377 and ASTM protocols. The experimental phase commenced with basic geotechnical characterization of the peat soil, including determination of moisture content, specific gravity, Atterberg limits, organic matter, fiber content, and pH value. Each test was selected based on its relevance to peat soil properties and was performed using calibrated equipment. Calibration records were maintained to ensure accuracy and confidence in the results, following standards where applicable. The Standard Proctor Compaction Test was conducted to identify the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), which served as foundational parameters for subsequent mechanical testing. The Unconfined Compressive Strength (UCS) Test was carried out to evaluate the load-bearing capacity and strength development of the stabilized soil under axial loading. Similarly, the California Bearing Ratio (CBR) Test provided essential insights into the soil's bearing resistance, particularly under unsoaked conditions due to equipment constraints. Both tests were performed with strict adherence to BS 1377 standards, and their respective loading rates, durations, and calibration details were documented to enhance result reliability. To investigate the soil-fiber-additive interaction at the microscale, Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDX) was employed. This technique enabled morphological and elemental characterization of the

treated peat matrix. The sample preparation process, sputter coating parameters, and operational settings of the SEM equipment were described to ensure methodological transparency. The numerical modelling phase utilized SIGMA/W and SLOPE/W (GeoStudio application) to simulate the deformation and stability behaviour of reinforced peat embankments. Input parameters for the models were derived from laboratory findings, particularly those from UCS and CBR tests. SIGMA/W was applied for stress-deformation analysis, while SLOPE/W was used to calculate the factor of safety for slope stability. Calibration and mesh sensitivity checks were conducted to validate the model output, ensuring confidence in the simulation results.

In summary, this chapter has provided a full account of each experimental technique, including justifications for test selection, testing protocols, limitations, and equipment calibration. The methodology framework established here lays a solid basic for the analysis and discussion of results in subsequent chapters. To ensure consistency, accuracy, and repeatability of the experimental procedures, all laboratory and field tests were conducted in accordance with established international standards. Table 3.6 summarizes the tests performed in this study along with their corresponding reference standards.

Table 3.6: Summary of Test Methods and Reference Standards

Test Name	Purpose	Reference Standard / Source
Moisture Content	Determine the natural water content of peat	BS 1377: Part 2: 1990
Specific Gravity	Measure the density of soil particles	BS 1337: Part 2: 1990
Bulk Density	Calculate the mass per unit volume of the soil	BS 1337: Part 2: 1990
pH Measurement	Assess the acidity or alkalinity of the peat	BS 1377: Part 3: 1990
Organic Content	Quantify organic matter in peat using loss-on-ignition	ASTM D2974-87
Fiber Content	Classify peat as fibric, hemic, or sapric	ASTM D1997-13
Unconfined Compressive Strength (UCS)	Determine the compressive strength of stabilized peat	BS 1377: Part 7: 1990
California Bearing Ratio (CBR)	Evaluate the bearing capacity of subgrade soil	BS 1377: Part 4: 1990
Atterberg Limit	Determine the consistency and plasticity characteristics of soil	BS 1377: Part 2: 1990
Field Vane Shear Test	Estimate in-situ undrained shear strength	BS 1377-9:1990
Standard Proctor Test	Determine the optimum moisture content	BS 1377: Part 4: 1990
Scanning Electron Microscopy (SEM)	Analyse microstructure of treated peat	Goldstein et al., 2017 (SEM Protocols)
Energy Dispersive X-ray (EDX)	Identify and map elemental composition of samples	Standard EDX Laboratory Procedures

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the research work which covers numerous physical, mechanical, and microstructural analyses of fiber-reinforced peat with traditional and non-traditional stabilizers in comparison with control and reinforced peat mixtures. The effect of adding various percentages of rubber crumb, rubber powder and resin in the form of calcium-based powder (SH-85) in the peat-cement mixtures on the strength development of the treated specimens will also be discussed individually in this chapter. The results were then tabulated and graphed to demonstrate the correlation between the reinforced-peat mixtures and the variables tested.

To meet the aims of the current study, numerous basic properties tests, compaction by Standard Proctor and mechanical testing of UCS and CBR were carried out. The findings of these basic properties test contribute to developing a relationship between peat properties and the additives used. In this study, the targeted strength of peat is 345 kPa that is specified by the ASTM D4609 standard. Thirty-five (35) design mixes have been developed, prepared, and tested for shear strength in accordance with ASTM standards. All the basic property tests and strength tests in this study were performed at the University Malaysia Sarawak's Geotechnical Laboratory (UNIMAS). The following sections outline the basic characteristics and mechanical tests performed on the design mixes.

4.2 Physical and Mechanical Properties of Untreated and Treated Peat

The basic properties of the peat were determined in the laboratory, including moisture content, Atterberg limit, specific gravity, pH, fiber content and organic content. Mechanical properties that have been investigate in this study are the Unconfined Compressive Strength (UCS) tests and California Bearing Ratio (CBR) tests that reported in the next section. The collected findings were then used to determine the optimum design mixture.

4.2.1 Evaluating the Physical Properties of Untreated Peat Soil

Field vane shear test has been carried out at the site at Kampung Endap, Kota Samarahan where the peat sample was collected. It is one of the most common in-situ tests to be carried out at the site to estimate the undrained shear strength of soil. The vane shear test was carried out at 3 different spots at Kampung Endap, at a depth from 0.5 m to 3.0 m into the ground as shown in Figure 4.1. The relationship between the undrained shear strength and the depth of the studied soil layer is illustrated in Figure 4.2. The average strength of the peat increases with depth is due to the effective stress acting on the lower layer of soil. The peat sample used in this study is 16.0 kPa where the sample was dug at the depth of 1.0 m.

The reliability of the vane shear test results in this study is supported by the nature of the soil. Sapric peat, being highly decomposed and low in fibrous content, presents a relatively uniform and cohesive matrix, making it suitable for vane shear testing. According to Ahmad Afip et al. (2019), vane shear testing performed on similar sapric peat in Meranek, Sarawak, yielded consistent undrained shear strength values and demonstrated strong correlations with peat properties such as salinity and density (R^2 = 0.84 and 0.94,

respectively). Further confirmation from their study affirmed that Sarawak's peat that classified as H7 to H8 on the Von Post scale was exhibited properties well-aligned with the test's application. When carried out under controlled procedures and site consistency, the vane shear test is a reliable and credible method for assessing shear strength in Sarawak's sapric peat.

To recognize the category of the studied soil, Von Post classification system test was carried out to investigate the degree of decomposition during the peat sampling. The von Post scale is a valuable tool for identifying peat based on its fibre content and the degree of humification or decomposition associated with it. The Malaysian Soil Classification System for Engineering Purposes and Field Identification (Huat, 2004; Veloo et al., 2014) classifies peat based on its organic content and degree of humification. On the Von Post humification scale, the nearly complete decomposition of the examined peat is classified as H8. The studied peat is classified as Sapric or amorphous peats, which are extensively decomposed peats with a high proportion of amorphous material and an extremely unclear plant structure. The composition of the peat is pasty and very dark brown in colour. When squeezed between the fingers, approximately two-thirds of the peat escapes and a small amount of dark pasty water released. The plant material that remains in the hand is consist of decomposable remnants such as roots and fibers as shown in Figure 4.3. The compositional analysis of peat shown in Table 4.4 indicates high organic content and low fiber content that categorized the peat as Sapric. In this study, the soil layer of 0.5 m to 1.5 m is classified as sapric or amorphous peat as the fiber content obtained is less than 33%. As demonstrated in Table 4.4, the peat sample has 11.98% fibre. This result indicates that the peat is low in fibre as defined by ASTM D4427.



Figure 4.1: Field Van Shear test

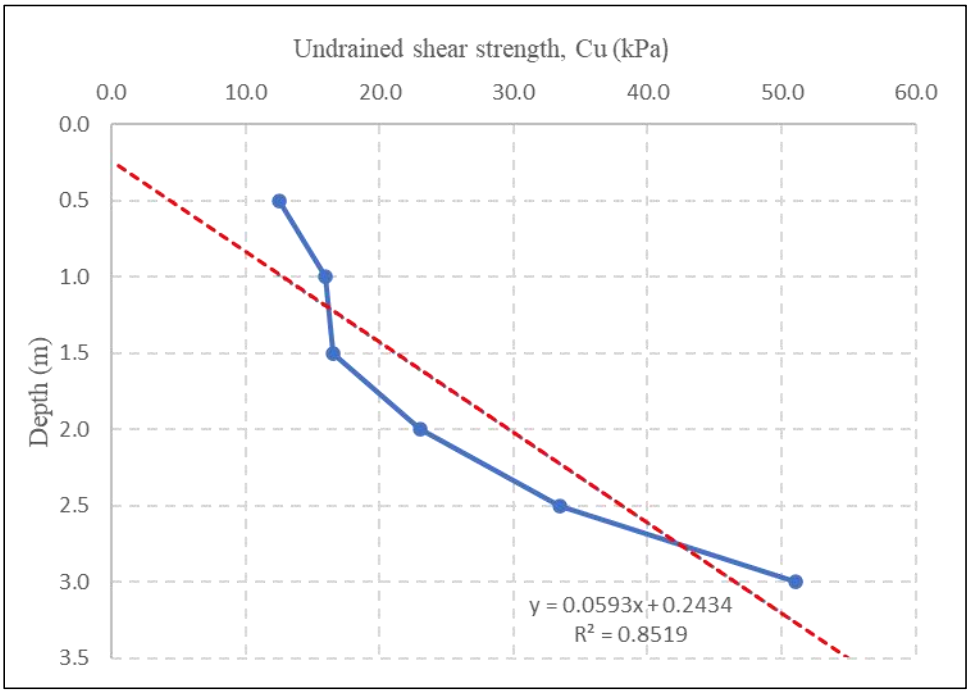


Figure 4.2: Undrained shear strength



(a) Test in progress (b) Sample after squeezed

Figure 4.3: Von Post degree of humification

Among other organic soils, peat possess undesirable engineering characteristics including excessive compressibility, low strength, and long-term settlements. This peat soil was readily identifiable at the location due to its dark to dark-brown colour, musty odour, and highly compressible. To determine the organic content of the peat, three sets of peat samples were heated to a furnace set at 450°C until no substantial change in mass occurred, as specified in ASTM D2974 2014. The peat under examination exhibits a relatively high organic content of 86.83%.

The Ignition Loss Test, also referred to as the organic content test, was performed to determine the mass of peat sample that underwent combustion in a muffle furnace. The results are expressed as a percentage of the total mass of the peat sample. The results

below indicate that the peat sample contains a high proportion of organic matter. What left in the porcelain dish was a fine-grained substance known as ash that is a by-product of the combustion of peat samples. Occasionally, the chemical composition of ash differs according to the combustion method. The average organic content that roughly of 86.83 %, indicating that the sample contains a high amount of organic matter. The results of the organic content analysis are important in classifying peat and other organic soils. Thus, peat collected from Kampung Endap has a high organic content of more than 75%, classifying it as peat (Kolay & Taib, 2018).

Besides, the fiber content (or fabric of organic soil) is typically calculated as the dry weight of fibres retained on the 150-micron openings of a #100 mesh sieve (0.15 mm aperture size), expressed as a percentage of the oven-dried mass. The fibres are classified as fine (woody or nonwoody) or coarse (woody) and have a diameter of 0.15 mm (Veloo et al., 2014). To assess the fibre content of the peat samples, they were immersed in a dispersion agent (5% sodium hexametaphosphate) for a duration of 15 hours, following the guidelines of ASTM D1997 2013. The sample's estimated fibre content was within 11.98% after they were oven-dried at 110 ± 5°C and rinsed through a No. 100 filter.

The ratio of unit weight of peat to unit weight of water is referred to as the specific gravity of peat. Because it is a ratio, it has no unit, even though it is necessary to determine the soil's weight-volume relation. Gs is defined in BS 1377: 1990 as the ratio of the mass of soil particles in the air to the mass of de-aired distilled water in the air. However, water is being replaced in this test using kerosene, as dry peat might be lighter than water. The kerosene used in this test has a specific gravity of 0.82. The specific gravity test using a small pycnometer that placed in a vacuum desiccator for at least 1 hour determined the

specific gravity of the peat to be 1.67. When compared to other forms of soil, this indicates that the unit weight of the peat sample is comparatively small and 'lightweight.'

Moisture content has a crucial role in determining soil qualities such as compressibility, workability, strength, and settlement. A series of wet peat samples were weighed and then dried in an oven at a temperature of not more than 110ºC. After drying, the weights are the weights of soil solids. As a result, the weight changes that occurred during drying are equal to the weights of water, resulting in moisture content. In this study, the natural moisture content of the peat is 580.20%, which is within the range of 200% to 2207% in East Malaysia, reported by Huat (2004). Peat has high water-holding ability, as seen by the moisture content value. Moreover, the higher organic matter resulted in a comparatively high moisture content of Sarawak peat. According to the previous research, the spaces between organic particles have a great potential for entrapping moisture, resulting in the high moisture content of peat.

Table 4.1: Von post classification system (after Karlsson and Hansbo 1981) Adapted from (Khanday et al., 2021)

Designation	Group	Description
Fibric (Fibrous peat)	H1 - H4	Low degree of decomposition. Fibrous structure. Easily recognizable plant structure, primarily of white masses
Hemic (Semi-fibrous)	H5 - H7	Intermediate degree of decomposition. Recognizable plant structure
Sapric (Amorphous)	H8 - H10	High degree of decomposition. No visible plant structures. Mushy consistency

Table 4.2: USDA peat classification (adapted from Huat, 2004)

Type of peat	Fiber content	Von Post scale
Fibric peat	Over 66 %	H4 or less
Hemic peat	33 – 66 %	H5 or H6
Sapric peat	Less than 33 %	H7 above

Table 4.3: Malaysian soil classification systems (MSCS) for peat

Soil Group	Organic Content	Group Symbol	Subgroup Symbol	Degree of Humification	Subgroup Name	Field Identification
Peat	> 75%	Pt	Ptf	H1-H3	Fibric or fibrous	Dark brown to black in colour. Material has low density so seems light. Majority of mass is organic, so if peat is fibrous, the whole mass will be recognisable plant remains. If highly humified, the peat will be more likely to smell strongly.
			Pth	H4-H6	Hemic or moderately decomposed peat	
			Pta	H7-H10	Sapric or amorphous	

Table 4.4: Summary of Basic Properties of Sapric Peat

Peat Soil Parameters	Units	Value	Remarks
Degree of decomposition	-	H8 (Sapric)	Highly decomposed peat indicates low fibrous content, high compressibility, and poor drainage, necessitating chemical stabilization (Khanday et al., 2021)
Natural Moisture Content (w_c)	%	580.20	Extremely high moisture content contributes to low shear strength and significant settlement risk; typical of tropical peat (B. B. K. Huat et al., 2014).
Acidity (pH)	-	3.00	Strongly acidic environment may hinder cementitious reactions and pozzolanic bonding, reducing the efficiency of ordinary stabilizers (Duraisamy et al., 2009)
Fiber Content (F_c)	%	11.98	Low fiber content suggests high humification and limited tensile reinforcement, supporting the use of synthetic or rubber additives (Zulkifley et al., 2013)
Ash Content (A_c)	%	13.17	Moderate ash content indicates partial mineral presence, which can slightly aid pozzolanic reactions when binders are introduced (Zainorabidin & Wijeyesekera, 2007b)
Organic Content (O_c)	%	86.83	Very high organic content impedes cement hydration and results in weak cement-soil bonds, reinforcing the need for tailored stabilizer combinations (Kazemian et al., 2011b)
Specific Gravity (G_s)	-	1.67	Low specific gravity reflects organic dominance and low mineral content, typical of problematic peat soils (B. B. K. Huat et al., 2014).
Liquid Limit (Natural State)	%	434.00	Extremely high, indicating poor workability, high plasticity, and significant volume change behaviour; stabilization is essential (B. B. K. Huat et al., 2005).
Liquid Limit (Dry State)	%	114.40	Still high after drying, showing residual plasticity and confirming the need for both moisture reduction and particle bonding interventions.
Vane Shear	kPa	9 to 19	Very low undrained shear strength, typical of Sarawak peat; insufficient for supporting loads without reinforcement or stabilization (B. B. K. Huat, 2004)

4.2.2 A comparative analysis of the physical characteristics of peat in Sarawak

The physical characteristics of peat obtained from Kg. Endap, Kota Samarahan, and its comparison with peat collected from other parts of Sarawak, including other areas in Kota Samarahan, Matang, Batu Kawa, and Sg. Bidut, Sibu, are listed in Table 4.5. The peat recovered from this study exhibits a significant level of humification. The humification level of H8 classifies it as sapric. Upon comparison with peat from other regions, it can be determined that the peat under investigation is mature peat that has undergone greater decomposition, similar to the peat discovered in Kota Samarahan 1 and Sg. Bidut (Amuda et al., 2019; M. E. Mohamad et al., 2022). Additional studies have identified both fibric and hemic peat in various locations (Aminur et al., 2009; M. Sa'don et al., 2015). In accordance with the results of the index tests listed in Table 4.5, the peat under investigation is highly humified and contains less fibre. This is due to the peat's fibre content of 11.98%, which was determined to be among the lowest in comparison to other regions. Moreover, it was determined that the organic matter content in the peat of Sungai Bidut, Matang, Batu Kawa, and Kota Samarahan surpassed 75%. This supports the claim that each of these soils is composed exclusively of peat, in accordance with the standards outlined in ASTM D1997-25 where peat is defined as a soil whose organic content surpasses 75%. ASTM D2974 similarly categorises Kg Endap peat as peat with a low ash content. Similar to peat recovered from previously studies, the specific gravity of Kg Endap peat was low. The primary factor contributing to a low specific gravity is the existence of organic substances, which inherently have a lower specific gravity. This ultimately resulted in a general decrease in the specific gravity of the peat soils. In comparison to the peat in other regions, the pH value of peat at Kg Endap is the lowest, indicating that the peat is highly acidic by nature.

Table 4.5: A comparative analysis of the physical characteristics of peat found in the Sarawak region

Physical Properties	Kg. Endap, Kota Samarahan	Kota Samarahan 1	Kota Samarahan 2	Batu Kawa, Kuching	Matang, Kuching 1	Matang, Kuching 2	Sg Bidut, Sibu Peat	Remarks
Moisture Content (%)	580.20	378–620	426–817	607–926	594–856	360.72-787.04	953–1484	Moisture content of peat at Kg. Endap aligns with typical ranges for tropical peat but is lower than the values recorded in Sg Bidut, Sibu (953–1484%). The extremely high moisture in Sg Bidut reflects a more saturated and potentially floating peat condition, which poses greater challenges for stabilization and compaction (B. B. K. Huat et al., 2014). Meanwhile, Matang and Batu Kawa peats also demonstrated wide moisture variation, likely due to different water table depths and decomposition levels (Amuda et al., 2019).
Specific Gravity	1.67	1.69–1.71	1.25–1.67	1.11–1.34	1.08–1.35	1.45–1.82	0.53–0.69	The specific gravity in this study was 1.67, which is within the upper range for tropical peat but significantly higher than the 0.53–0.69 observed in Sg Bidut. This suggests that Kg. Endap peat may contain more inorganic particles or exhibit less degradation compared to the highly fibric and decomposed peat in Sibu (Kazemian et al., 2011b). The lower Gs in Sg Bidut is indicative of very loose, lightweight organic matter with minimal mineral composition, indicating high degradation and decomposition (Zainorabidin & Wijeyesekera, 2007b).
Organic Content (%)	86.83	92–96	89	95	95	66.60–78.88	85.95–95.40	The organic content recorded in this study (86.83%) is consistent with the values from other Sarawak peats (e.g., 85.95–96% in Sg Bidut and Kota Samarahan 1). These values confirm that all locations fall within the classification of highly organic peat, necessitating stabilization strategies that can cope with low shear

Table 4.5 Continued

								strength, high compressibility, and hindered pozzolanic reactions (Duraisamy et al., 2009).
Fiber Content (%)	11.98	3.5–6.2	23.2	50.3	45.6	32–65	58.49–63.24	Kg. Endap recorded a fiber content of 11.98%, which is notably lower than those from Batu Kawa (50.3%) and Sg Bidut (up to 63.24%). Lower fiber content suggests a more sapric peat, where organic matter is more decomposed. This affects its stabilization potential with lower fiber content generally results in reduced tensile resistance but may improve workability and binder interaction due to higher homogeneity (Zainorabidin & Wijeyesekera, 2007b).
Ash Content (%)	13.17	–	–	–	–	45–86	4.60–14.05	Only two sites reported ash content—up to 14.05% in Sg, Bidut, indicating poor mineral base (Bujang et al., 2005); and a significantly higher 45–86% in Matang Kuching 2. Higher ash content implies greater mineral content and improved potential for pozzolanic reactions during stabilization. Ash content of 13.17% in this study is within the range as in Sg Bidut and the relatively low ash supports its classification as organic-dominant peat, which may require additional pozzolanic or cementitious materials to achieve effective stabilization (Latifi, Horpibulsuk, et al., 2017a)
pH	3.00	–	3.4–4.3	3.3–3.9	3.2–3.8	4.05–6.18	3.07–3.30	The pH value at Kg. Endap was 3.00, among the lowest reported. This strongly acidic condition may inhibit cement hydration and reduce the efficiency of lime or cement-based stabilizers. Conversely, Matang Kuching 2 showed pH levels up to 6.18, indicating more favourable conditions for chemical stabilization (Kazemian et al., 2011a). The extreme acidity at Kg. Endap highlights the necessity for either pre-treatment or selection of acid-tolerant additives (e.g., SH-85 or fly ash blends).

Table 4.5 Continued

Von Post Classification	H_8	H_8–H_9	H_4	H_5	H_4–H_5	H_3–H_7	H_5–H_{10}	The peat at Kg. Endap was classified as H_8 (sapric), indicating high decomposition and low fibrous content. In contrast, other studies reported a range from H_4 to H_{10}, with sites like Batu Kawa and Sg Bidut encompassing both hemic and fibric layers. This confirms the greater homogeneity and higher decomposition state at Kg. Endap, potentially allowing more consistent stabilization response, but with reduced natural strength (Zainorabidin & Wijeyesekera, 2007b)
Author	**This study**	Amuda et al. (2019)	M. Sa'don et al. (2015)	M. Sa'don et al. (2015)	M. Sa'don et al. (2015)	Aminur et al. (2009)	M.E. Mohamad et al. (2022)	

4.2.3 pH Value of Untreated and Treated Peat

pH test is used to measures acidity or alkalinity of the soil, which is the concentration of hydrogen ions, H^+. The pH values of original and mixed peat samples were evaluated using an electrometric approach that provided direct readings of the pH values of the peat samples. The pH values of the test on original peat samples indicate that, peat in its natural state is acidic as the electrometric method yielded a value of 3.0. When compared to previous studies, (Sa'don et al., 2015) it is discovered that the pH level of Sarawak peat is between 3.0 to 4.0 which is acidic. Due to diversity of sites and natural decomposition processes, this influences the acidic characteristic of peat composition. The sampling area is an agricultural sector, which commonly involve peat burning during the dry season. Figure 4.4 depicts the varied pH values and the targeted pH value of 9 and shows that all the modified samples passed the recommended value. The pH value of the unreinforced peat, on the other hand, increased nearly fourfold with the addition of cement alone. Considering CaO is alkali-based, the presence of calcium oxide (CaO) in Portland cement is one of the reasons that contributed to the increase in pH value.

Tremblay et al. (2002) reported that the minimal pH required for soil stabilization with cement is 9 as no cement products form below this pH value. According to Rahgozar & Saberian (2016), the pH of the stabilized soil admixture must be greater than 9 for organic soil stabilization to be effective. According to this approach, since the overall pH value achieved is greater than 9, the minimum 5% of cement applied in this study is sufficient for successful soil stabilization to occur. Moreover, according to the findings of UCS and CBR tests, it can be generally observed that reinforced samples with a higher pH value exhibit greater strength. Regarding additions with SH-85, incorporating these

additives does not substantially alter the pH level of the modified samples in contrast to adding cement.

The pH values of the stabilized peat admixtures are evaluated immediately after they are mixed in this study. The addition of cement to the peat resulted in a substantial increase in pH to 10.12, nearly 3.5 times higher than the pH of untreated peat. Nevertheless, the introduction of SH-85 into the peat throughout all the samples resulted in a gradual rise in pH as the amount of additives increased. Furthermore, the inclusion of 5% to 15% of rubber crumb (RC) and rubber powder (RP) resulted in a pH increase of approximately 3% to 6%. The inclusion of 12% SH-85 in all the samples examined results in an increased pH value of up to 12.79. All the evaluated design mixes exceeded the pH criteria of being greater than or equal to 9 which is adequate to use as a stabilization mixture for construction.

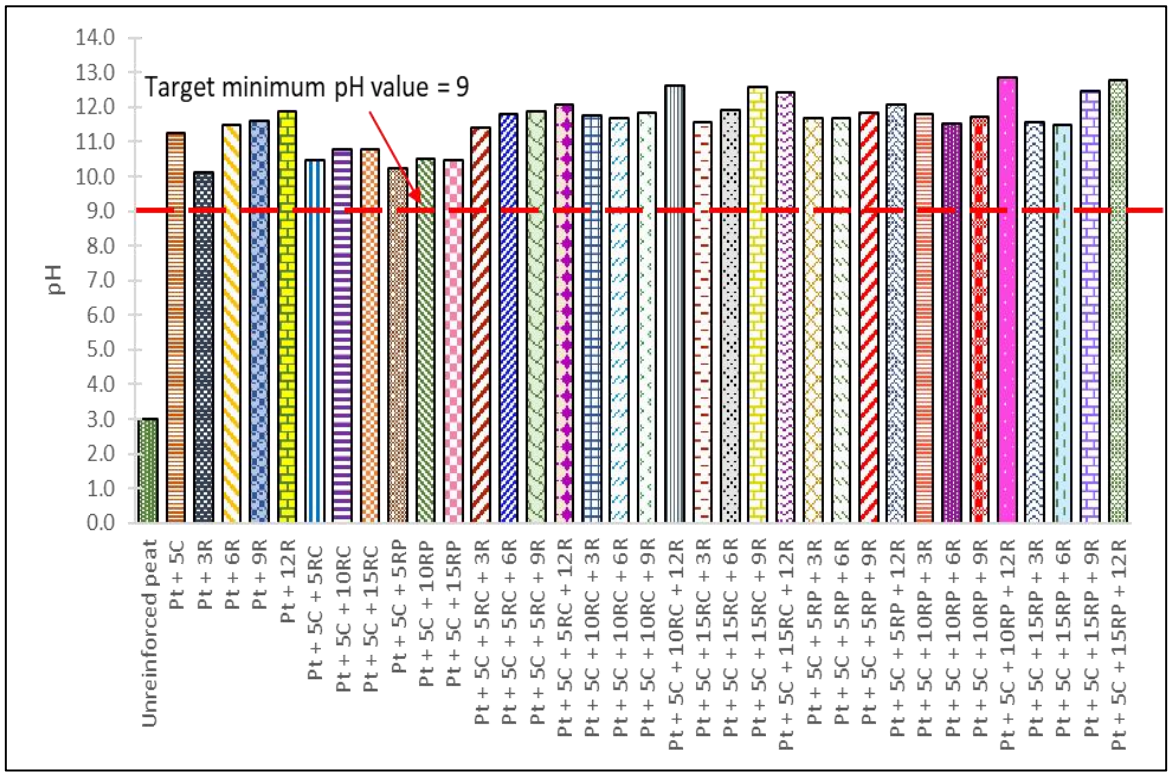


Figure 4.4: pH of studied design mixture

4.2.4 Effect of Stabilization on MDD and OMC of Peat

A series of Standard Proctor tests were performed to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the peat itself as well as the modified design mixtures (reinforced samples). According to the results, the addition of cement, rubber crumb, rubber powder and SH-85 influences the moisture level of the mix, with the moisture content varying based on the percentage of additives. These various percentages of additives have an impact on the MDD value as well. The moisture-density connection for all the samples is shown in Figure 4.5 to Figure 4.7, respectively.

The Standard Proctor test is used to determine the untreated peat maximum dry unit weight at the optimum moisture content. During the compaction process, the sample was placed in the compaction mould in three layers, with the last layer filling the mould and collar. Each layer of samples was compacted 25 times in total. For the untreated peat, the test was repeated 11 times to acquire the result of a consecutive drop in weight of the peat sample. Figure 4.5 illustrates a graph of dry unit weight versus moisture content for the untreated peat from the study area. The compaction curve obtained from the Standard Proctor test for untreated peat demonstrates a distinctive double peak, indicating two separate points where maximum dry density is achieved at different moisture contents. The peat sample has a maximum dry unit weight, γ_{dmax}, of 5.98 kN/m^3 and an optimum moisture content, w_{opt}, of 38.5% as shown in Figure 4.5. This type of graph is known as a double peak compaction curve because it yields two maximum dry densities and two optimum moisture contents (Razouki & Kuttah, 2020). This phenomenon, although not

typical in mineral soils, is recognized in highly organic soils like peat, which exhibit nonlinear and complex compaction behaviour due to their unique physical and microstructural properties.

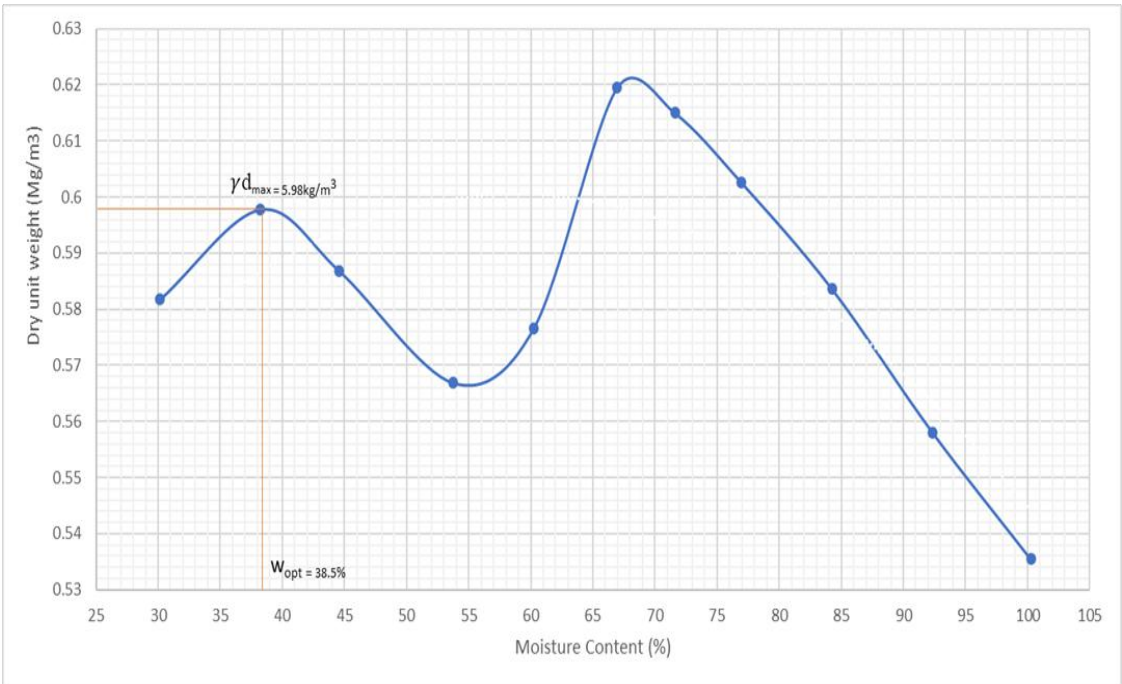


Figure 4.5: Compaction test by Standard Proctor for peat

Untreated peat is characterized by its high organic content, high natural moisture, low density, and significant compressibility, all of which contribute to the non-standard behaviour observed during compaction. According to Huat et al. (2005), peat contains a mixture of decomposed plant material, fibrous structures, and colloidal organic particles, which respond non-uniformly to increasing moisture and compactive effort.

According to Lee & Suedkamp (1972), a double peak curve is unusual but not rare where the sample's liquid limit is less than 30% or greater than 70%. This study complied with the theory because liquid limit of natural peat in the study area is approximately 114.4%. This double peak compaction curve can be classified as irregular soil types as

stated by Zeng et al. (2018) in their study. Muhardi et al. (2019) also reported a one-and-a-half peak graph in a peat soil compaction test in Rimbo Panjang, Indonesia.

Soil samples with these liquid limit ranges (less than 30% or greater than 70%) tend to generate odd shapes, such as a double peak curve. The first peak occurs when the moisture content is low. When the peat is dry, the surface friction is higher, resulting in a high shear strength but a low dry density. The first peak, observed at approximately 38.5% moisture content with a dry unit weight of 5.98 kN/m^3, corresponds to the initial densification of the partially saturated peat matrix. At this stage, the moisture content facilitates particle lubrication, reduces interparticle friction, and allows the fibers to rearrange under compaction, leading to a localized maximum in dry density. However, beyond this point, an increase in water content reduces the soil's bearing capacity due to the rise in pore water pressure and the lubricating effect of excess water, causing a temporary drop in dry density.

When more water is added to the peat, the particles become lubricated, resulting in an increase in dry density. In untreated peat soil, the initial addition of water leads to lubrication of organic particles and a reduction in interparticle friction, facilitating improved rearrangement under compactive effort. This results in an increase in dry density up to the optimum moisture content (OMC). However, beyond the OMC, further water addition typically reduces dry density due to increased pore water pressure and saturation. The dry density will continue to rise until the second peak of optimum water is reached. The occurrence of the second peak, at a significantly higher moisture content which is 68%, is attributed to the reorientation and collapse of fibrous structures within the peat. At elevated water contents, organic colloids swell, and entrapped gases and voids are

displaced, allowing finer particles to settle and fill voids between larger fibers. This results in secondary densification and a subsequent rise in dry density. This behaviour has been reported in earlier studies, where untreated fibrous peats show similar secondary peaks due to internal structural adjustments at high moisture levels (Kuttah, 2024; Mesri & Ajlouni, 2007).

This behaviour is particularly relevant for tropical peat soils, which are inherently fibrous and hydrophilic. Although Kazemian et al. (2011b) provide a detailed review of peat's geotechnical properties, including its high compressibility and moisture sensitivity, they do not directly address the double-peak phenomenon. However, their findings support the broader understanding that peat's unique microstructure allows for significant internal rearrangement under load, particularly when influenced by moisture. The observed compaction behaviour highlights the necessity of employing customised stabilisation methods that consider peat's non-linear moisture–density relationship and its susceptibility to structural changes in high moisture environments. Moreover, Mesri & Ajlouni (2007) emphasized that in natural peat, the variation in decomposition levels (e.g., sapric vs. fibric content), degree of humification, and initial structure can significantly influence compaction characteristics. A double peak curve in such soils reflects this heterogeneity, and it highlights the difficulty in identifying a single optimum moisture content due to the multi-phase compressibility behaviour of peat.

In summary, this phenomenon as first detailed by Lee & Suedkamp (1972), emerges from internal structural adjustments within the soil matrix as moisture increases, leading to two distinct optimal moisture contents. In organic soils like peat, this is attributed to the rearrangement and lubrication of fibrous components at elevated water

contents, which enhances particle alignment and facilitates a secondary densification phase. Similar behaviour has been reported by Kuttah (2024), who identified dual peaks in the compaction curve of clayey soil, corresponding to differing degrees of moisture-induced plasticity and reorientation. These findings align with the broader understanding that fiber-rich soils do not conform to the typical single-peak compaction curve due to their unique microstructure and high moisture retention, thus requiring careful interpretation during field compaction and stabilization processes. Therefore, this double peak phenomenon is not indicative of experimental error but is a valid and important observation of the compaction behaviour of untreated peat. It underscores the need for tailored geotechnical analysis when dealing with organic soils, where standard compaction theories developed for mineral soils may not fully apply.

In this compaction test, the initial peak was identified as the maximum dry density. The first peak, which yielded the highest dry density, reflected the peat in its most natural state when it was first compacted. After reaching the initial peak, the peat is recompacted, and the particle arrangement is disrupted and rearranged in a different way resulting the second peak to occurred (Zeng et al., 2018). Since the purpose of the compaction test is to determine the optimum moisture content of natural peat, the first peak values are preferred because it reflects the natural peat particle properties without being damaged.

As for the stabilised peat, data in Figure 4.6 shows peat with 5% cement and 5% rubber crumb has the highest MDD of 805 kg/m^3 and OMC of 27% for the control samples. Besides, the mixture of peat, 5% cement, 10% rubber crumb and 6% SH-85 shows the highest MDD value of 798 kg/m^3 and OMC of 39% for the reinforced samples group. It's indicated that as the percentages of rubber crumb increase, the value of MDD decreases.

This is due to the sample's density decreasing when peat mixes with rubber crumb. As a result, raising the percentages of rubber crumb increases the peat's optimum moisture content. This, in turn, reduces the MDD of the peat indirectly. The distance between the rubber chips and soil particles reduces as the rubber crumb content increases, contributing to an increase in volume and a decrease in dry density. The presence of cement also contributes to the peat becoming denser as compared to the uncemented specimen. Furthermore, reinforced samples with rubber crumb as demonstrated in Figure 4.6 shows that the addition of additive (SH-85) influences the MDD value of the reinforced peat. As the percentages of resin increase, MDD value also increase for the addition of 3% and 6% of the additive. However, the MDD demonstrated a decrease when 9% SH-85 was integrated into almost the entire composition of the design mixture and unexpectedly, the MDD increased by approximately 0.43% to 7.34% when 12% SH-85 was added. The occurrence may have taken place because the combination of cement and water induces hydration, thereby modifying the peat's dried density. In addition, the hydration of the design composition is expedited by the calcium content of SH-85. In general, a decline in OMC is associated with a progressive increase in MDD for both the control and modified samples.

Based on Figure 4.7, the incorporation of rubber powder (RP), cement (C), and SH-85 stabilizer (R) into peat (Pt) mixtures exhibits varying effects on the compaction characteristics, particularly in maximum dry density (MDD). As shown in Figure 4.7, rubber powder demonstrates a pattern of variability and inconsistency in its MDD and OMC results. While the inclusion of cement and SH-85 significantly enhances the MDD due to the densification and bonding effects from hydration products (Z. A. Rahman et al., 2016), the addition of rubber powder shows limited contribution to strength improvement.

This limitation is attributed to the fine particulate nature of RP, which acts more as a filler than a structural reinforcer, resulting in a non-uniform and fluctuating compaction behaviour.

The graph illustrates a noticeable improvement in MDD for mixtures such as Pt+5C+5RP+12R, indicating that SH-85 plays a substantial role in increasing dry unit weight when used synergistically with cement. However, samples containing only RP show irregular compaction curves and lower peak densities, suggesting minimal interaction or bonding between RP and the organic peat matrix. This observation aligns with findings by Hilwane et al. (2021), who reported that finer rubber particles may reduce density but fail to significantly reinforce soil structure without sufficient cementitious agents.

Thus, it can be concluded that while RP contributes to altering the compaction profile, its effectiveness is maximized only when complemented with stabilizers like cement and SH-85. The optimal performance, both in terms of compaction and dry density, is observed in ternary blends rather than binary mixtures with RP alone. Consequently, in this study, samples that include rubber crumbs are more practical and reliable for reinforcing peat soil.

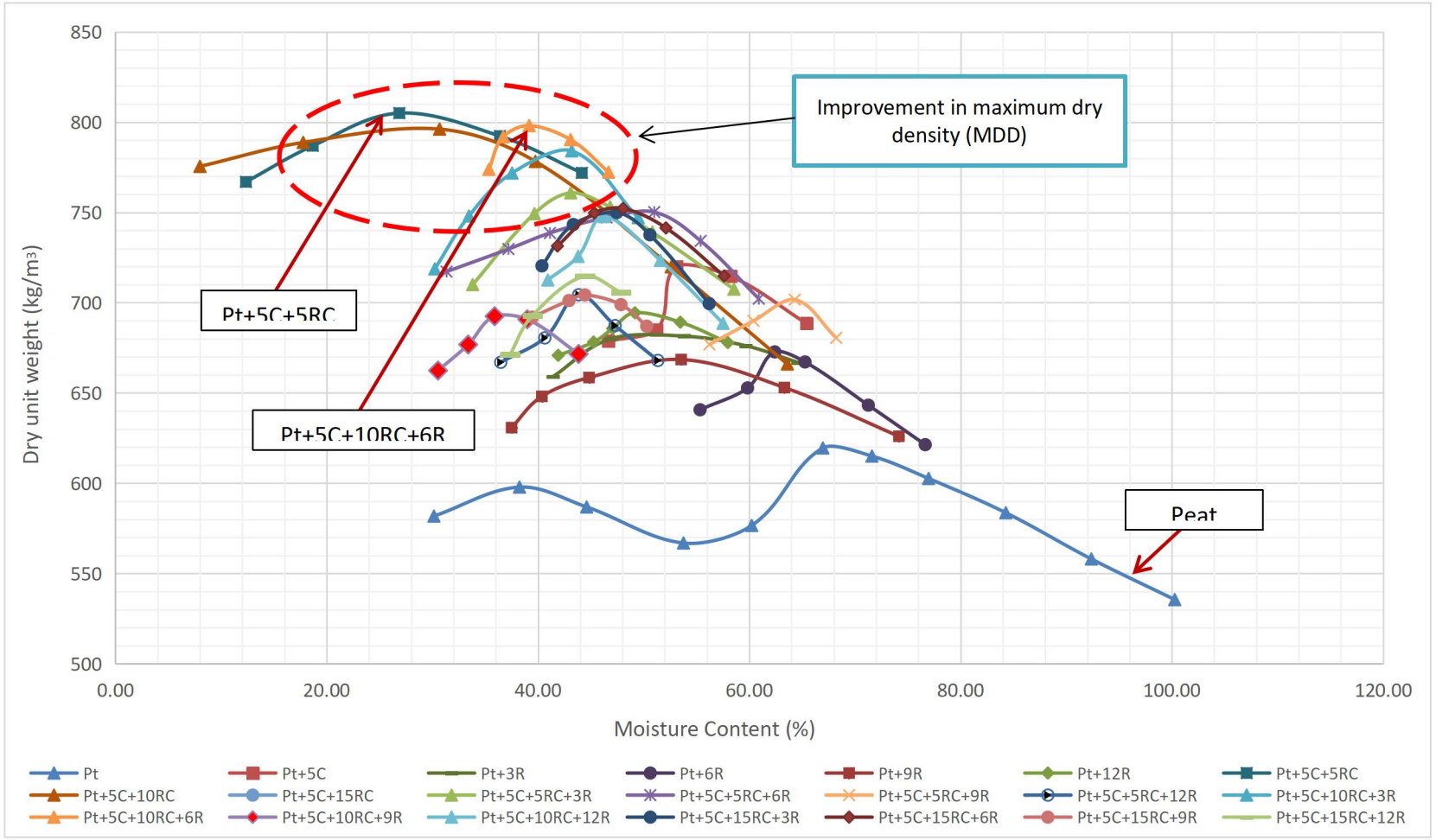


Figure 4.6: Compaction test by Standard Proctor for control samples and modified samples with RC

*Footnote: Pt - peat, RC - Rubber crumb, RP - Rubber powder, R - SH-85

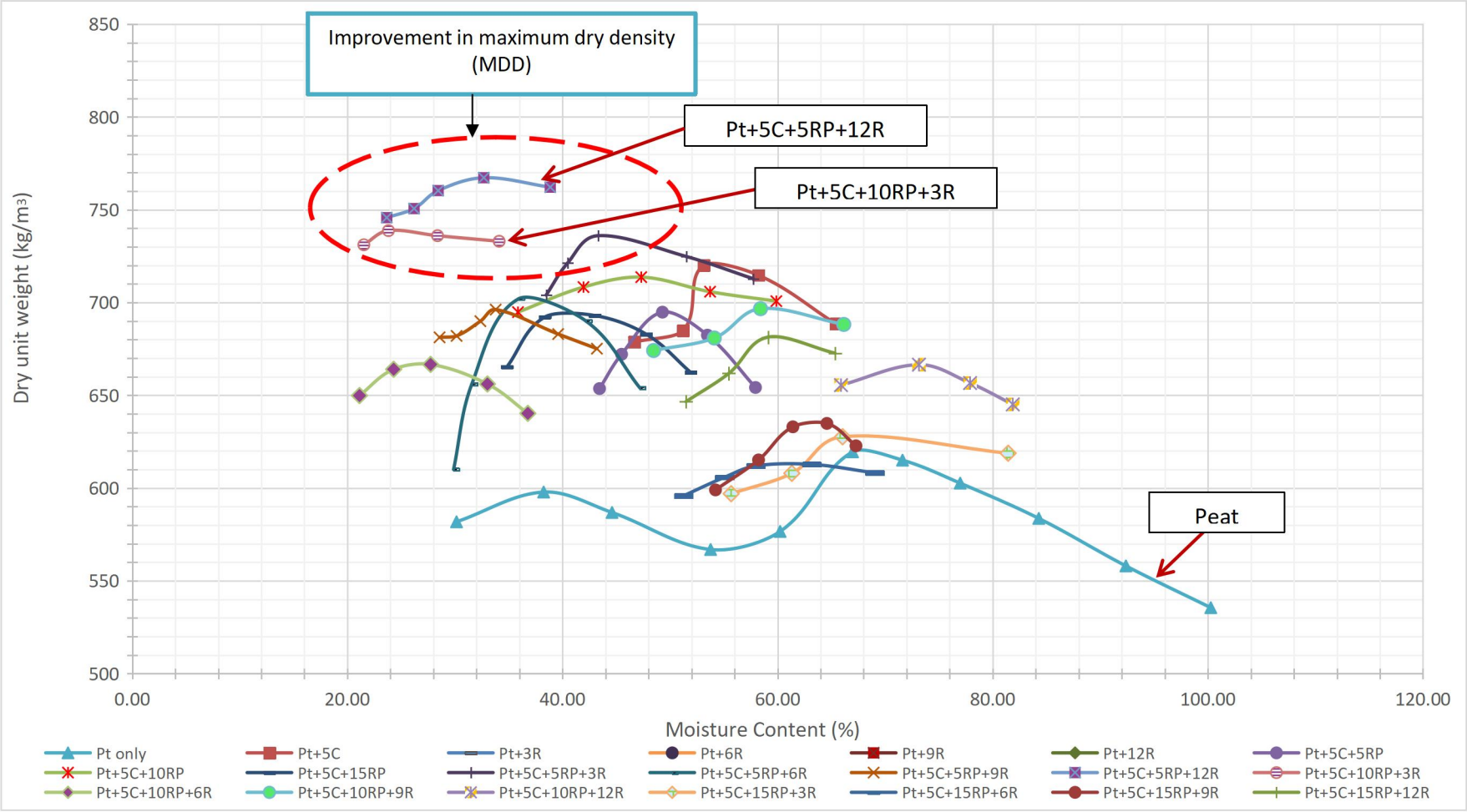


Figure 4.7: Compaction test by Standard Proctor for control samples and modified samples with RP

*Footnote: Pt - peat, RC - Rubber crumb, RP - Rubber powder, R - SH-85

4.3 Unconfined Compressive Strength (UCS) test

In this study, the UCS test was performed in compliance with BS1377 Part 7: 1990. The objective of this experiment is to ascertain the impact of cement, rubber crumb, rubber powder, SH-85, or a combination of these materials, on the development and strength of the soil. For each day of the curing period, three samples are prepared, and the highest value among these three samples will be designated as the achieved value. Figures 4.8 to 4.14 exhibit the UCS results for various design mixes throughout a 7, 28, and 56 day curing period. At 11.2 kN/m^2, natural peat has the lowest value. It is understandable that the low strength is a result of the natural peat's high moisture content, which results in a high compressibility. Peat's strength is increased through the addition of reinforcement material, binder, and additive, as shown in the figures. The compressive strength behaviour of the stabilized samples shows that RC consistently outperforms RP across all curing periods. At 7 days (Figure 4.8), RC-modified samples already exceeded the minimum UCS requirement of 345 kPa, reaching up to 398.9 kPa for the mixture of peat + 5% cement + 10% rubber crumb + 3% SH-85. Additionally, at 7 days curing period, design mix of peat + 15% rubber crumb + 6% SH-85 and peat with 5% cement + 15% rubber crumb and 3% SH-85 also shows significant increment in the strength with 293.6 kN/m^2 and 252.3 kN/m^2 respectively.

In contrast, RP-modified specimens (Figure 4.9) demonstrated insufficient strength, remaining well below the required threshold. This trend continued at 28 days (Figures 4.10 and 4.11), where RC again surpassed the UCS benchmark, peaking at 376.1 kPa, while RP samples still underperformed. However, the addition of 15% rubber crumb and 15% rubber powder with 9 and 12% SH-85 to the design mixture resulting in a lower strength not only after 7 days of curing, but also after 28 and 56 days of curing time. This occurs due to the

modification of aggregate grading in the mixtures by rubber particles, leading to the formation of additional voids. Due to the rubber particles failure to fill the voids in the aggregate, the specimen becomes more porous, lowering its strength (Bashar et al., 2017). A notable performance was observed at 56 days (Figures 4.10 and 4.11), where RC-modified specimens reached peak UCS values of up to 513.3 kPa (Peat+5% cement+15%RC+6%SH-85) indicating strong long-term strength development. Meanwhile, RP achieved its highest strength at 161.9 kPa (Peat+5% cement+5%RP), while most other mixes containing RP remained below the benchmark. The broader spread and steeper slope of the RC stress–strain curves also imply higher stiffness and greater energy absorption capacity compared to RP, which showed flatter curves and earlier strain softening.

The strength development for all the design mixture is illustrated in Figure 4.10 and Figure 4.11. From the figures, it shows that for 28 days of curing, almost all the design mixtures that contains RC exhibit an increase in shear strength, with peat stabilized with 5% cement + 10% RC shows an increasing value of 64% from 7 days curing to 342.4 kN/m^2. Furthermore, the modified sample of 5% cement + 15% RC + 6% SH-85 exhibiting the highest value of 376.1 kN/m^2. This provides around 28% of the strength increase compared to the 7^{th} day of curing period. This is followed with peat + 5% cement + 10% RC + 3% SH-85 (330.6 kN/m^2), which increases its strength by approximately 39%. The peat stabilized with 5% cement, 15% RC and 6% SH-85 achieves a maximum strength value of 513.3 kN/m^2 after a curing period of 56 days. Following this, the mixture of peat and 3% SH-85 achieves a strength value of 466.4 kN/m^2 that surprisingly increased about 450% from 28 days curing period. Furthermore, the inclusion of 3% and 6% of SH-85 into the peat results in greater improvements in strength compared to the addition of 9% and 12% SH-85. This demonstrates that a minimal quantity of SH-85 is adequate for stabilizing

peat. However, none of the mixture that contains rubber powder surpasses the threshold value of 345 kPa. The strength value exhibited fluctuations and did not demonstrate any substantial value during the observed curing period. From the results, it can conclude that incorporating SH-85 resin into the mixture improves the long-term strength of the soil. The addition of rubber crumb to the mixture with SH-85 resin might expedite the development of strength, particularly during the initial 28 days of the curing process. During the 56-day curing period, six of the thirty-five design mixtures show significant strength development in the reinforced peat and were able to achieve the 345 kPa threshold value. When using rubber crumb, one-third of the design mixture (5 out of 15) demonstrates an increase in strength value.

These findings align with previous studies highlighting the reinforcement potential of coarser rubber particles in stabilizing soft soils. According to Edil & Bosscher (1994), rubber shreds and larger particles tend to form better interlocking networks with soil grains, which enhances shear resistance and compressive behaviour. Moreover, the time-dependent gain in UCS supports arguments by Foose et al. (1996), who reported that rubber–cement-soil mixture improve over longer curing periods due to progressive hydration and pore refinement. On the other hand, the underperformance of RP in most samples can be attributed to its finer size and potentially weaker bonding with the soil matrix, which may hinder the formation of a mechanically robust skeleton. While Liu et al. (2020) acknowledged the compatibility of RP with cementitious systems, their findings also warned that excessive fines might act as fillers rather than active reinforcers in organic soils.

The result of the investigation indicates that cemented peat specimens exhibit a significant effect of brittle behaviour on the soil structure. With the rapid decline followed

when the tested specimen achieved its maximum strength, an immediate breaking point with no apparent plastic deformation or energy absorption can be identified. Rahgozar & Saberian (2016) also report a similar condition in their study regarding to this behaviour.

In summary, rubber crumbs and rubber powder that is used in the design mix in this study were supposed to act as a reinforcing agent, enhancing the soil's strength and bearing capacity (M. Sa'don et al., 2018). The strength growth of reinforced peat utilising rubber crumb with traditional and non-traditional stabilizer can be observed after 28 and 56 days of curing. The increasing trend in the UCS values was attributed to the rubber crumb's reinforcing characteristics. It prevents the sample from cracking and binds the soil particles together, resulting in an increase in the stabilised soil's UCS values. Rubber crumb is used to fill the small pores in the peat structure, enhancing the soil's ductile behaviour while also increasing the compressive strength of the design mix (M. Sa'don et al., 2021). Additionally, by adding SH-85 and cement as a binder, it significantly enhances the strength of reinforced peat to exceed the threshold of 345 kPa from ASTM D4609 criteria. Furthermore, the study showed that addition of SH-85 had a significant stabilizing impact on the peat specimens, with UCS values increasing as the curing period was increased. However, the addition of rubber powder into the design mixture did not surpasses the requirement threshold of 345 kPa. The test results indicated that the inclusion of rubber powder and SH-85 within reinforced soil leads to a decrease about 8 – 27% in the compressive strength in five out of twelve design mixtures for 56 days curing period but another seven-design mixture shows an increased in strength for about 41 – 349%. Moreover, it improves the cement-soil's brittle behaviour to a more ductile one. However, the inclusion of rubber powder does not show any significant value as it just acts as a filler and not be able to reinforce the peat soil even when SH-85 is added into the mixture.

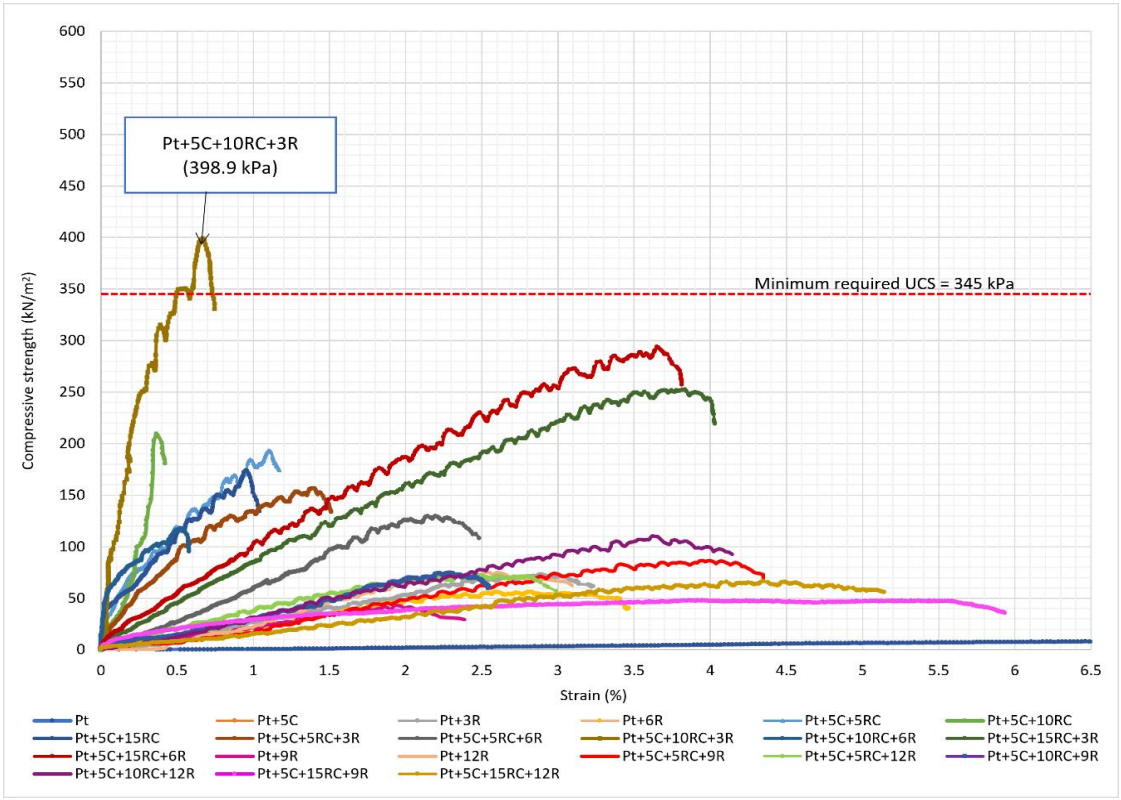


Figure 4.8: Stress – Strain Relationship for modified samples with RC (7 Days)

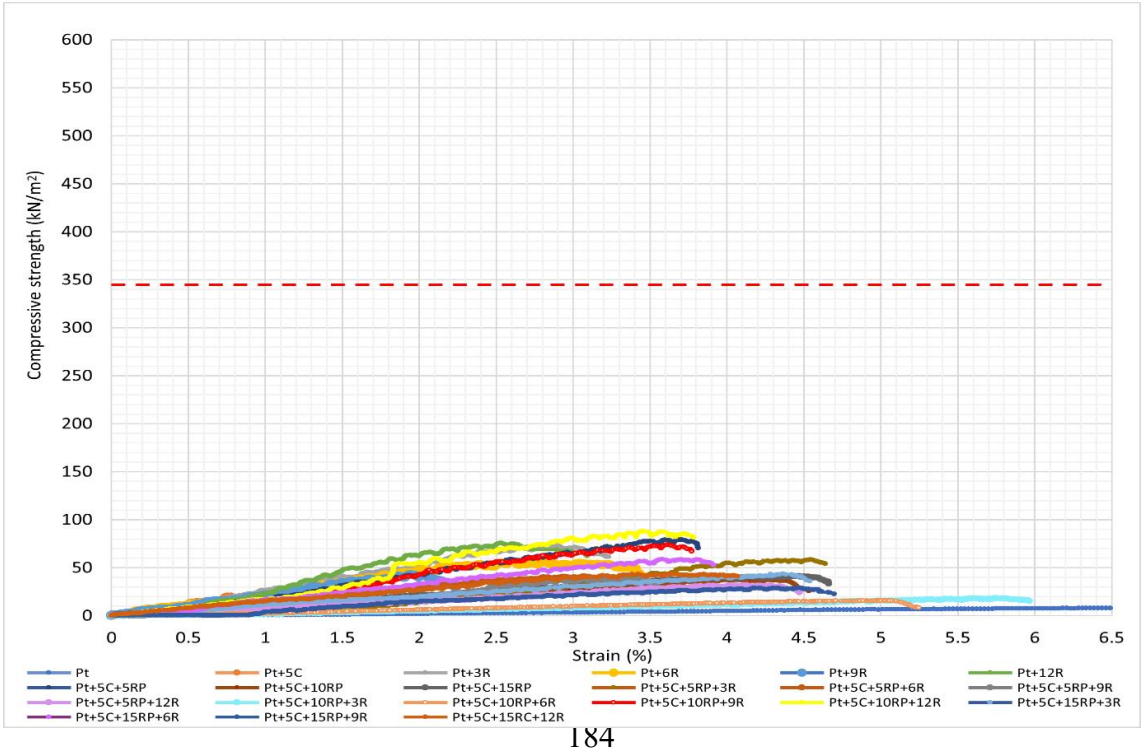


Figure 4.9: Stress – Strain Relationship for modified samples with RP (7 Days)

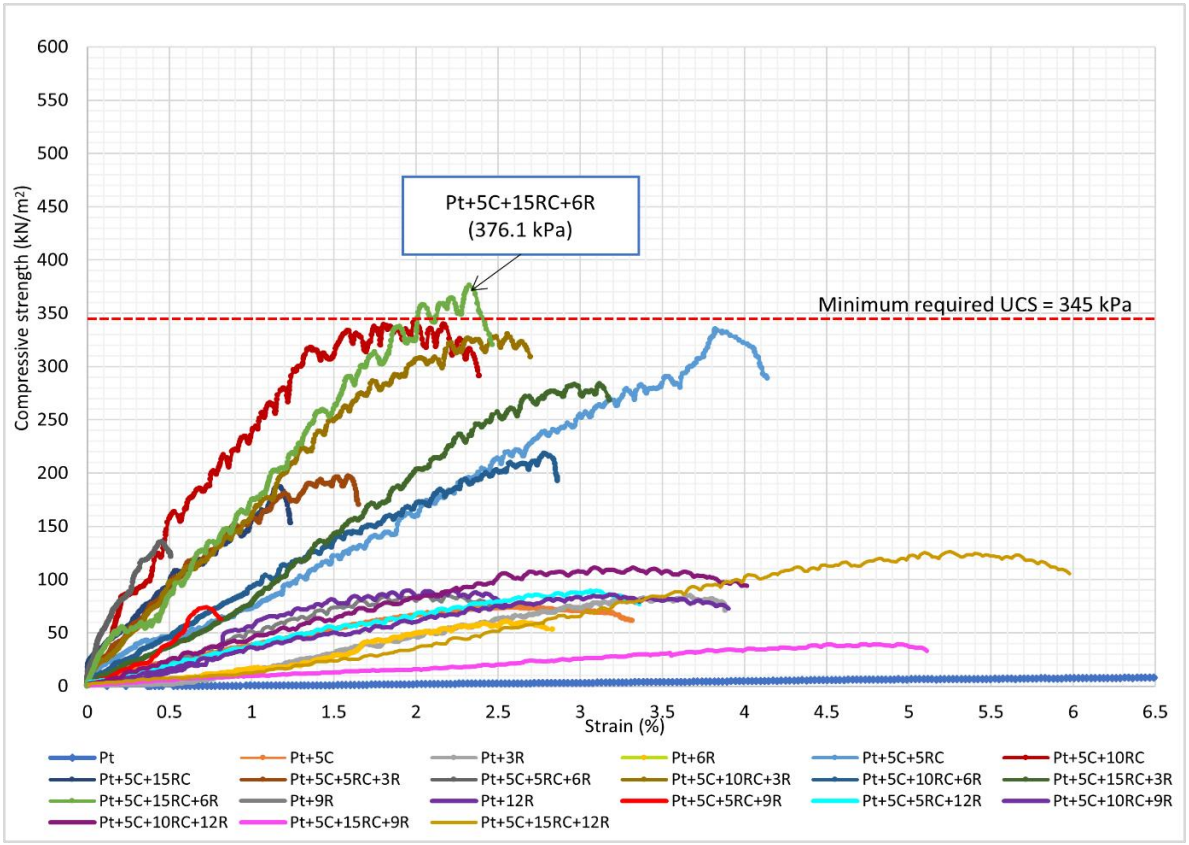


Figure 4.10: Stress–Strain Relationship for modified samples with RC (28 Days)

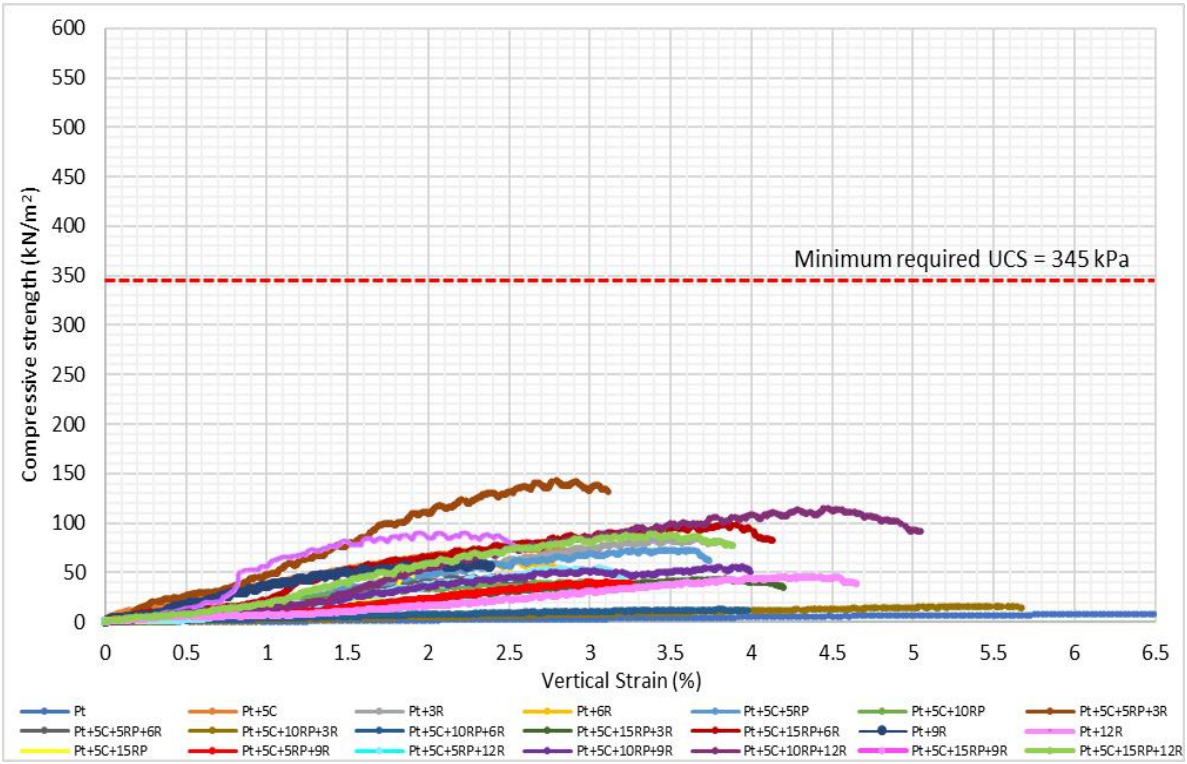


Figure 4.11: Stress – Strain Relationship for modified samples with RP (28 Days)

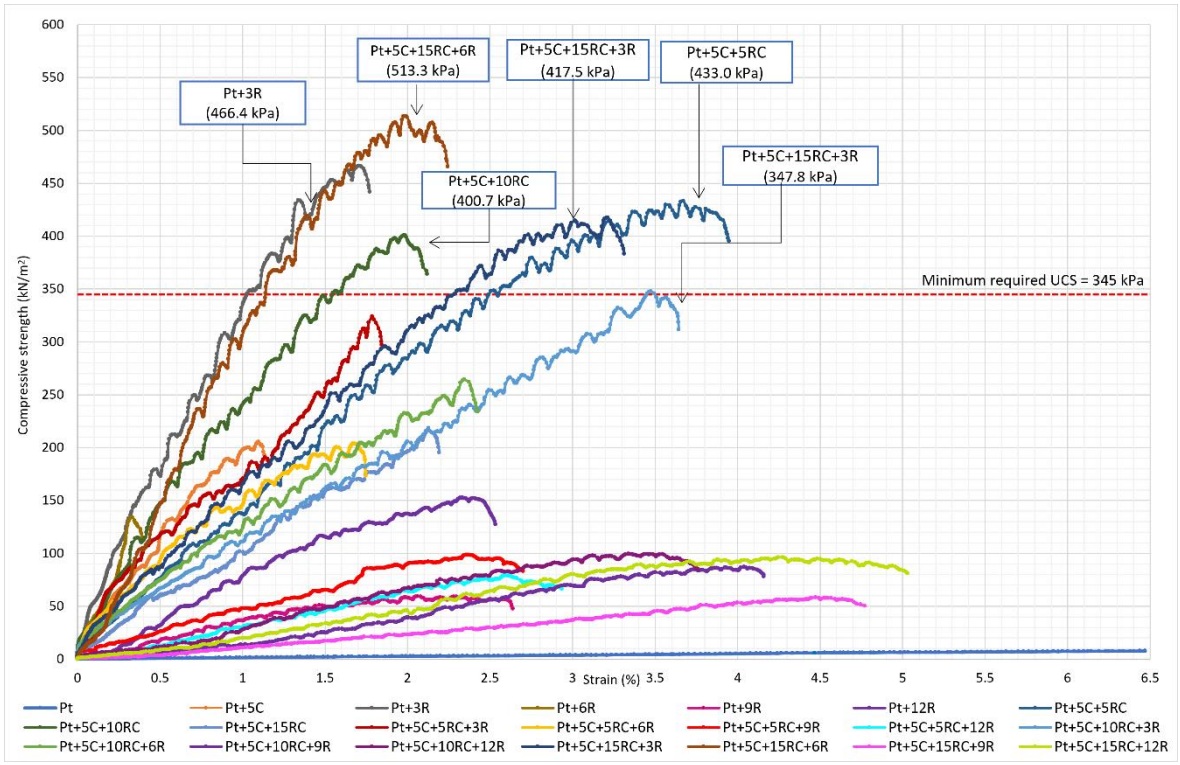


Figure 4.12: Stress – Strain Relationship for modified samples with RC (56 Days)

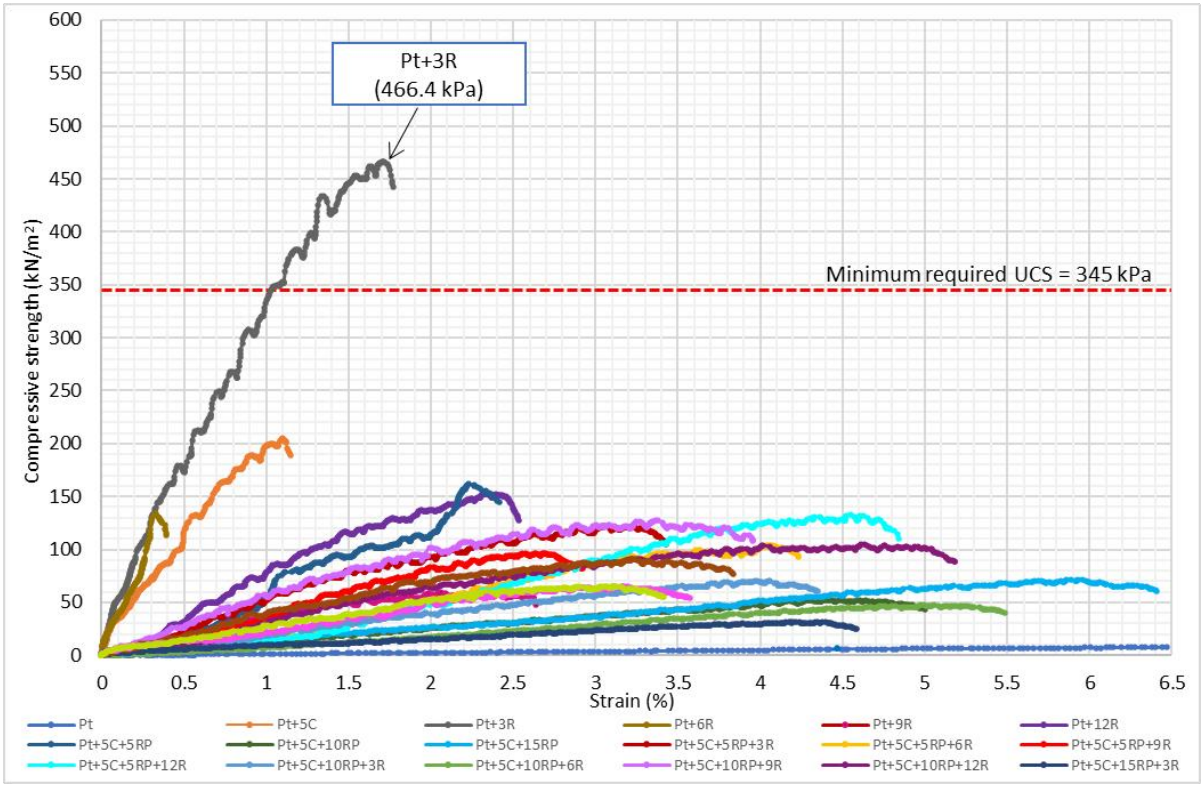


Figure 4.13: Stress – Strain Relationship for modified samples with RP (56 Days)

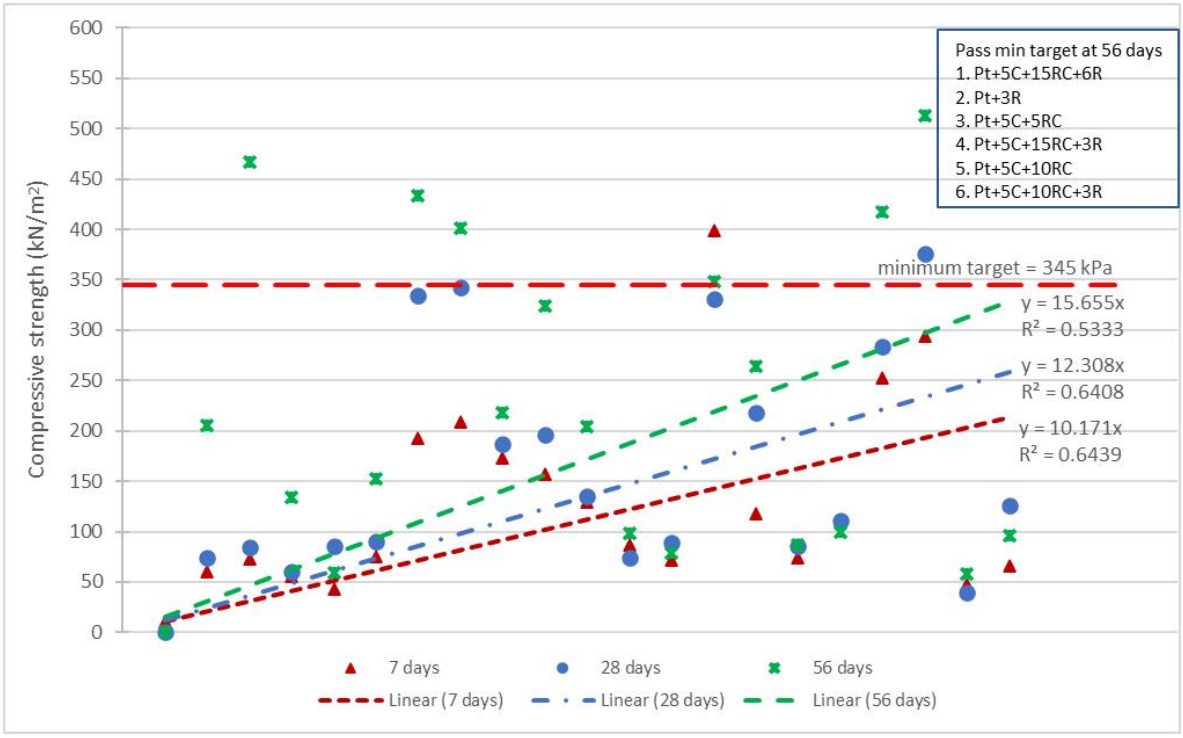


Figure 4.14: Strength development of modified samples with RC

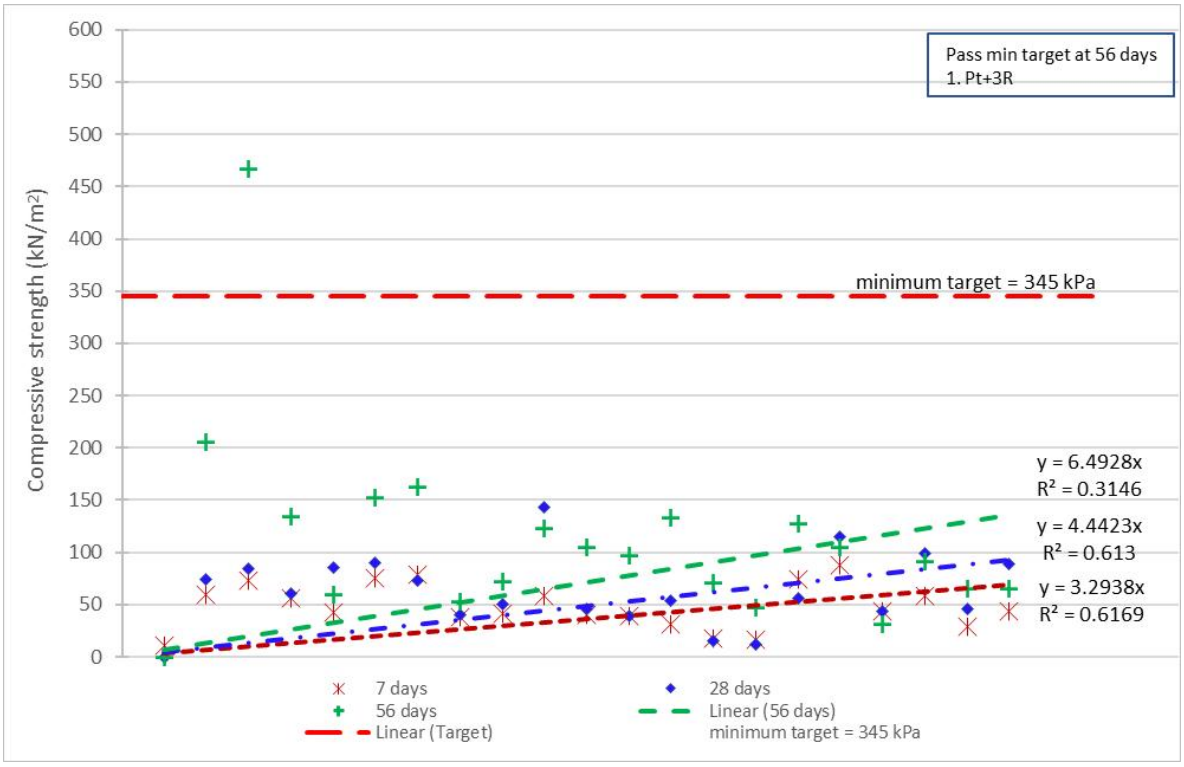


Figure 4.15: Strength development of modified samples with RP

The coefficient of determination (R^2) is an important statistical measure used to evaluate the strength and reliability of a regression model. It indicates the proportion of the variance in the dependent variable as the compressive strength in this study, that can be predicted from the independent variable, namely curing time. An R^2 value closer to 1.0 represents a stronger linear correlation, whereas a value closer to 0 signifies a weaker relationship. According to established guidelines, R^2 values above 0.7 are considered good, values between 0.5 and 0.7 indicate a moderate correlation, and values below 0.5 are generally regarded as weak (Cohen, 2013; Hair et al., 2023).

In Figure 4.14, which displays the compressive strength data for stabilized peat samples with RC, the linear regression analysis yields R^2 values of 0.6439 for 7 days, 0.6408 for 28 days, and 0.5333 for 56 days. These values suggest that the linear model explains a moderate to good proportion of the variance in compressive strength, especially in the early curing periods. The regression model adequately fits the 7-days and 28-days data, suggesting a predictable strength development during the initial curing period of the stabilized peat mixtures. The slightly lower R^2 value at 56 days (0.5333) may reflect increased variability in strength gain over time due to interactions between the cementitious additives, reinforced materials, and the organic nature of the peat.

Conversely, Figure 4.15 presents the compressive strength results for stabilized peat samples with RP. In this figure, the R^2 values obtained from the linear regressions are 0.6169 for 7 days, 0.6130 for 28 days, and 0.3146 for 56 days. The 7-day and 28-day R^2

values suggest a moderate correlation between curing time and strength gain, although not as strong as those seen in the stabilized mixes with RC. However, the 56-day R^2 value of 0.3146 indicates a weak correlation, implying that the strength progression at later stages is inconsistent and difficult to predict. This may be attributed to the behaviour of rubber powder that only can act as a filler, which limits the development of internal bonding or pozzolanic reactions typically responsible for continued strength enhancement.

The comparison between the two figures highlights that treated peat with RC exhibit superior strength performance and more consistent regression behaviour over time. The inclusion of cement and other reinforcement components enhances not only the overall strength of the material but also the predictability of its behaviour, as evidenced by higher R^2 values. In contrast, treated peat with RP demonstrates inconsistent strength performance at later curing stages, highlighting the need for proper soil stabilization to meet the minimum engineering strength requirements, such as the target value of 345 kPa at 56 days for practical applications. Hence, the strength development analysis using coefficient of determination (R^2) can serves as a quantitative confirmation of the positive impact of stabilization techniques on both the mechanical properties and the reliability of peat used in geotechnical engineering.

4.4 Failure Modes of UCS samples

Figure 4.16 shows the example of unconfined compressive strength (UCS) test specimens before being tested while Figure 4.17 and Figures 4.18 (a) – (f) shows the specimen after testing have been done. The compressive failure modes of peat can be influenced by the structural anisotropy manifested in peat because of organic matter and fiber (O'Kelly & Pichan, 2013). The untreated peat exhibited multiple fractures and an

unidentifiable failure plane, as evidenced by the failure pattern of the UCS samples depicted in Figure 4.17. This is due to the characteristics of amorphous/ sapric peat, which is decomposed peat known for its high organic content, low fiber content, and a soft texture. In comparison to hemic and fibric peat, it possesses more decomposed material and has a lower tensile strength than fibrous peat (Huat, 2004). The existence of fibers in peat results in enhanced compressibility, frictional resistance, and anisotropy. Conversely, amorphous peat deposits exhibit lower anisotropy, friction angle, and compressibility (Huat, 2004; Ibrahim et al., 2014; Zainorabidin & Mansor, 2016).

Nevertheless, visible fractures were identified in the peat that had been treated, as depicted in Figure 4.18 (a)–(f). A failure of the shear plane fracture, along with central bulging, has been observed in the specimen of cemented soil illustrated in Figure 4.18 (a). Figure 4.18 (b) depicts a 45° shear along a single plane that began at the upper part of the specimens but did not extend to the bottom. The addition of SH-85 to peat results in an improvement in its brittleness. Additionally, the 45° shear of the cemented peat containing RC and RP is illustrated in Figure 4.18 (c) and (d). In contrast, the specimen of cemented peat containing RP inclusion exhibited a central bulge and was more fragile. When SH-85 is added to the cemented peat with RC, as shown in Figure 4.18 (e), the width and length of the failure crack decrease, and it forms a 45° shear along a single plane from the bottom of the specimens while exhibiting good plastic failure.

The application of RC to peat results in an increase in the cracking intensity of the treated peat. These fissures release energy and allow the specimen to fail ductile rather than brittle (Wahab et al., 2021; Wang & Song, 2015), whereas the addition of resin increased the strength of the design mixture over a longer curing period. According to Kazemian et al. (2011a), the inclusion of fibers in peat alters its strength characteristics by

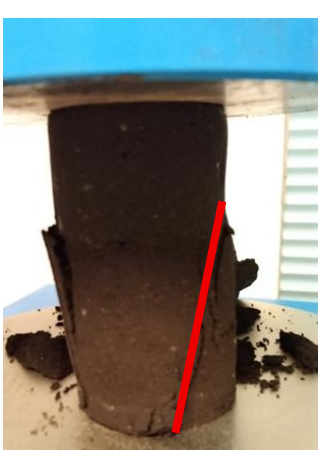
acting as reinforcement and generating effective stress in areas where it is lacking, resulting in anisotropy. Figure 4.18 (f) illustrates the detailed mechanism in which the cemented peat specimen fails when RP and SH-85 are included. The specimen exhibits nearly vertical cracks that extend from the bottom to the higher part. The crack grows as its length increases. The specimen additionally displays prominent bulges that are observable from the sides of the sample. The results indicate that rubber materials induce ductile behaviour in peat. This occurs due to the predominantly spherical shape of the rubber powder particles with smaller sizes, making them more susceptible to dislocation and sliding. Conversely, the larger particles are mainly fragmented, allowing for greater occlusion and achieving a more effective shear effect. The primary factor contributing to the enhancement of shear strength in rubber-reinforced soil is an increase in cohesion (Z. Yang et al., 2020). The findings of this study indicate that the inclusion of rubber powder does not have a substantial impact on the strength of the cemented soil, regardless of whether SH-85 resin is included or not. This statement is corroborated by a prior investigation conducted by Soltani et al. (2019), which concluded that the size of rubber particles does not have a substantial impact on the enhancement of soil strength.



Figure 4.16: Example of unconfined compressive strength test specimen



Figure 4.17: Example of failure patterns of the untreated peat



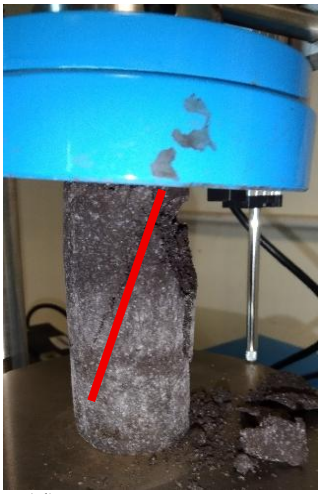
(a) Peat+Cement



(b) Peat+SH85



(c) Peat+Cement+RC



(d) Peat+Cement+RP



(e) Peat+Cement+RC+SH85



(f) Peat+Cement+RP+SH85

Figure 4.18: Example of failure patterns of the treated UCS samples

4.5 Effect of Treatment on California Bearing Ratio (CBR) Values of Treated and Untreated Peat Soil

The California Bearing Ratio (CBR) test results provide essential insight into the load-bearing capacity of both untreated and stabilized peat soils. The untreated peat sample exhibited a CBR value significantly below 5%, indicating that it is inherently weak and unsuitable for supporting structural loads without improvement. However, upon stabilization with cement, rubber crumb (RC), rubber powder (RP), and SH-85, a noticeable increase in CBR values was observed. Several treated mixtures recorded CBR values exceeding 5%, demonstrating marked improvement in strength and stiffness. According to the Public Works Department (PWD) Malaysia Road Design Manual (ATJ 5/85, JKR Malaysia, 1985), subgrade embankments for roadway classifications T1 through T5 must achieve minimum CBR values ranging between 5% and 12% to ensure adequate performance under traffic loading. Therefore, the treated peat samples meeting or exceeding this threshold can be considered suitable for use in road subgrades, particularly for low to moderate traffic applications. This enhancement confirms the effectiveness of the chosen stabilizing agents in transforming peat soil into a material with acceptable geotechnical performance.

For subgrade embankment applications, a California Bearing Ratio (CBR) test was conducted to study the strength effect and quantify the improvement of reinforced peat. To ensure test consistency, the reinforced peat is formed in a cylindrical metal mould with an internal diameter of 152 mm and a height of 178 mm. The specimens were prepared at the same MDD and OMC as the UCS test, with a 7- and 28-day dry curing period. Figure 4.19 shows the outcomes of employing cement, RC, RP and SH-85 to the studied peat. Based

on the figure, the addition of reinforcing agents greatly increased the CBR value in comparison to the untreated sample. Figure 4.21 illustrate the CBR value of the mixture when RC and RP are added, as the reinforcement increases the overall strength of the mixture. From the figure, 17 from 22 of the design mixes have exceeded the minimum CBR requirement of 5% for 7 days and 28 days of curing period, respectively. The addition of 15% RC and 5% SH-85 results in the highest CBR value at 32% and 42% after 7- and 28 days of curing period. For mix design of Pt+5%C+15RC+6%SH-85 the CBR value is rather high which is 12.9% for 7 days and 20.1% for 28 days curing period. The design mixture of Pt+5%C+15RC+6%SH-85 is chosen for the modelling in the next chapter as it comprises the highest compressive strength.

As shown in Figure 4.21, only one of the design mixtures containing rubber powder (RP) exceeds the minimum required CBR value. This result can be attributed to the inherent characteristics of rubber powder, which consists of fine, elastic particles that are generally non-bonded. While rubber particles may offer improved ductility and energy absorption, they may also reduce soil stiffness and load resistance when incorporated without optimal dosage or additional stabilizing agents. The soft nature of rubber does not provide a rigid matrix for load transfer, which could explain the lower CBR performance observed in some mixtures. This observation was supported by several studies. Alvarez et al. (2020) discovered that although rubber powder enhanced shear strength, its effect on CBR was minimal unless combined with other stabilizers. Similarly, study by Anglaaere et al. (2023) found that rubber particles were more effective in enhancing shear strength than CBR, indicating a selective influence on mechanical properties. Moreover, Ravichandran et al. (2016) demonstrated that CBR values improved up to an optimal 10% rubber content, after which further additions reduced performance. These findings reinforce that the effect

of RP on soil strength is highly dependent on dosage, soil type, and combination with other binders, emphasizing the importance of careful mix design for achieving desirable mechanical outcomes.

In this study, design mix with RC shows more convincing value as the characteristics of RC that can diminish the load on the foundation to improve the shear strength and other mechanical properties of the soil (Z. Yang et al., 2020). Increased in cohesion is mostly attributable to the increased strength of rubber-reinforced soil. The rubber crumb mixture's resistance is increased by the reinforcing characteristic. Granular rubber in the shape of longitudinal components leads to more effective reinforcement, improving strength and volumetric strain (Akbarimehr & Fakharian, 2021). The reinforcing is more effective with larger RC particles, enhancing the strength and volumetric strain of the RC soil mixture. The RC particles are generally fragmented and can better occluded, thus allowing for an improved shear effect. Granular rubber strengthens soil by encouraging strong adhesion between rubber and soil particles. Since coarse rubber particles have a bigger surface area of soil mixture, it provides additional reinforcement, enhancing the strength of the mixture.

As a result, peat reinforced with RC and SH-85 showed a significant increase in strength by exceeding the minimum specified CBR value of 5%. This indicates that the higher bearing capacity of the stabilized soil is not solely attributable to the cement hydration process, but also to the reinforcing effects of rubber and the pozzolanic activity of SH-85. The inclusion of rubber crumb enhances the ductility and frictional resistance of the soil matrix, promoting interparticle bonding and reducing deformation under load. Meanwhile, SH-85, a silica-rich biomass-derived additive, reacts with calcium ions

released from cement hydration to form additional cementitious products such as calcium silicate hydrate (C-S-H), further improving matrix strength and stiffness. These synergistic effects contribute to a more durable and resilient subgrade material.

By increasing the CBR value, the total thickness of the pavement can be reduced significantly, which has direct cost-saving implications for road construction. For low-volume roads, a minimum CBR value of 5% is often required by the Malaysian Public Works Department (PWD) to ensure adequate subgrade support and long-term serviceability. The treated peat in this study surpassed this threshold, reaching a CBR of 20.1% after 28 days, thereby not only meeting but far exceeding the design requirement. This performance enhancement suggests that chemically stabilized peat using rubber and SH-85 can serve as a viable subgrade replacement material, reducing the dependency on imported granular fill and supporting sustainable infrastructure development on marginal tropical soils.

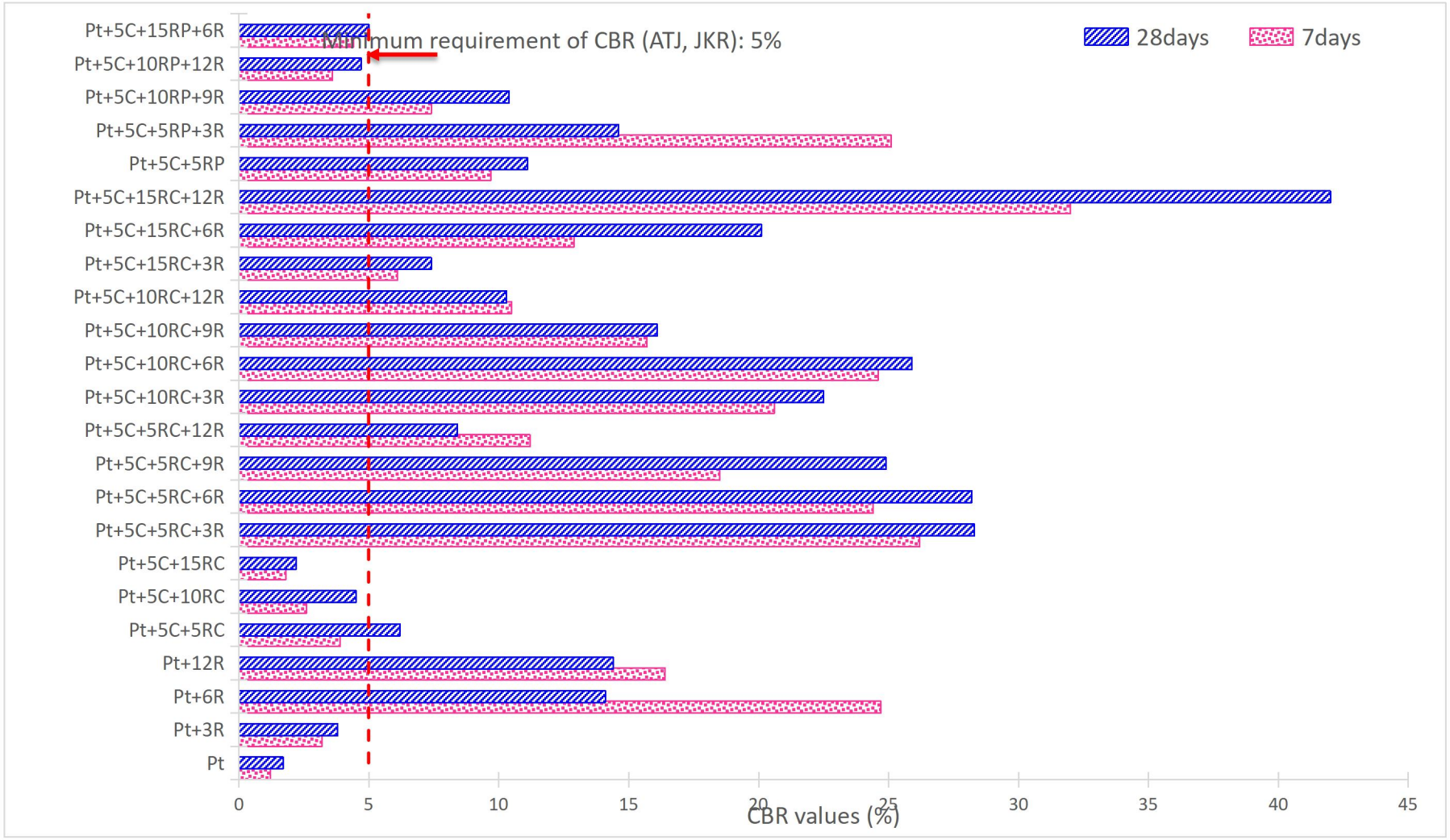


Figure 4.19: Performance of CBR on rubber crumb and SH-85

4.6 Microstructural Analysis - Scanning electron microscopy (SEM) & Energy-Dispersive X-ray Spectroscopy (EDX)

In this study, Scanning Electron Microscopy (SEM) coupled with Energy-Dispersive X-ray Spectroscopy (EDX) was employed to analyse the elemental composition of both untreated and stabilized peat specimens. The SEM-EDX (Energy Dispersive X-ray) technique provides elemental identification of materials captured in SEM images, thereby supporting mineralogical analysis. Scanning Electron Microscopy (SEM) is an advanced analytical technique widely used to investigate the surface morphology, microstructural characteristics, and topographical features of the soil while EDX is a microanalytical technique that identifies and quantifies elements present within a sample based on their unique X-ray emission spectra when excited by a high-energy electron beam (Goldstein et al., 2017).

To comprehend the spatial organisation and morphology of untreated and treated peat constituents, the Hitachi TM 4000 Plus Tabletop scanning electron microscopy was utilised in this study to image the microstructure of peat. Furthermore, using the EDX apparatus, the elemental composition of both untreated and treated peat is identified. Samples were chosen from the highest UCS results so that the microstructure of the soils could be evaluated using SEM micrographs and EDX experiments. Figure 4.21 – 4.23 illustrated the SEM micrograph of the treated and untreated peat. The SEM was employed to determine the microscopic structure of soil samples, and the microstructural differences between treated and untreated soil samples are easily noticeable. Samples were obtained for SEM analysis following the UCS tests conducted at 56 days. The grain size of the peat soil exhibited variability in size from small to large, as indicated by the microscopic image of its structure. The SEM image presented for untreated peat (with magnification 1000x)

clearly illustrates a heterogeneous microstructure, with particle sizes ranging from fine-grained organic particles to larger fibrous fragments. The image reveals densely packed clusters of fine particles embedded within a loose matrix of coarser fragments, and voids that suggest poor particle interlock. Such variability is a known characteristic of tropical peat, which typically comprises decomposed plant materials at various stages of humification, resulting in an inconsistent texture and gradation (B. B. K. Huat et al., 2005; Kazemian et al., 2011a). Additionally, the grain shape did not consistently comply to a round or pointed form. Most of the particles are spherical in shape, representing ground grain, with a small quantity of pointed shapes representing peat soil fibres. The microstructure under observation reveals colloidal microparticles that are homogeneous in nature. Peat exhibiting a colloidal microstructure is classified as amorphous granular material and falls within the H8 to H10 range according to the Von Post classification (Amuda et al., 2019).

Moreover, this microstructural evidence is corroborated by the Energy Dispersive X-ray Spectroscopy (EDX) analysis, which reflects the organic dominance of the material. The elemental composition table indicates high levels of carbon (C = 65.51%) and oxygen (O = 29.97%), confirming the presence of organic matter. The presence of trace elements such as aluminum (Al), iron (Fe), and lanthanum (La) further supports the notion that the particles vary not only in size but also in mineralogical composition, possibly resulting from minor inorganic inclusions or mineral coatings on organic particles.

This compositional diversity contributes to the physical variability in particle shape and texture, which further affects the mechanical behaviour of untreated peat. It also implies that the microstructure is influenced by both amorphous organic matter and

inorganic inclusions, adding another layer to the size and phase variability observed under SEM. Peat is composed primarily of pores, which have the capacity to retain a considerable quantity of moisture and generate an initial void ratio that is quite high. An observation can be made regarding the reduction in pore space volume within treated peat when compared to untreated peat.

Figure 4.20 presents the SEM image and Energy-Dispersive X-ray Spectroscopy (EDX) results for peat soil treated with 3% SH-85 additive and cured for 56 days compared with untreated peat. After 56 days of curing, SH-85-treated soil exhibits a formation of new mineralogical phases. The decrease in pore space is predominantly a result of crystallisation induced by the hydration process. The SEM micrograph shows a significant morphological transformation compared to untreated peat where particles appear more compact, and denser matrices can be observed, indicating structural reformation and possible cementitious product development. This morphological shift strongly suggests that a chemical reaction has occurred over time, likely due to pozzolanic activity induced by SH-85. The EDX spectrum and accompanying elemental composition table further support this hypothesis. The detected dominant elements are carbon (C = 66.44%), oxygen (O = 32.40%), and a trace but significant presence of calcium (Ca = 1.14%). The appearance of Ca is particularly important, as it is a primary component of many cementitious phases, including calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which are well-known binding products resulting from pozzolanic reactions between calcium-rich additives and silica/alumina present in organic soil (Barman & Dash, 2022; Horpibulsuk et al., 2009). The co-occurrence of Ca and O, supported by the compact morphology under SEM, implies the formation of new mineral phases, particularly C-S-H-like gels or crystalline compounds. The detection of trace silver

(Ag) is likely a background artifact or contamination, and its concentration (0.02%) is too low to contribute to any mineralogical significance. The change in microstructure and mineral composition after 56 days indicates that SH-85 facilitated chemical reactions within the peat matrix, leading to the formation of stable mineralogical products that enhance strength, reduce porosity, and improve soil stability. Such observations align with findings by Kazemian et al. (2011a), who reported similar mineral phase transformations in stabilized peat using various additives.

Figure 4.21 presents the SEM micrograph and EDX spectrum of peat treated with 5% cement, 5% rubber powder (RP), and 12% SH-85, cured for 56 days compared with untreated peat. The SEM image reveals a relatively dense and compacted microstructure with fewer visible voids and a smoother surface morphology compared to untreated peat or peat treated with SH-85 alone. This microstructural refinement suggests the formation of new binding compounds, likely due to chemical reactions among cementitious and pozzolanic components. The EDX elemental analysis substantiates this observation with a significant presence of calcium (Ca = 5.24%), silicon (Si = 2.16%), aluminum (Al = 0.88%), and oxygen (O = 37.06%), alongside dominant carbon (C = 53.35%), which is expected due to the organic nature of peat and rubber. Higher Ca content (5.24%) in this samples implying a more substantial formation of calcium-based hydration products. The coexistence of Ca, Si, and Al, along with elevated O levels, is a clear mineralogical signature of pozzolanic reaction products such as Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H). These hydration products are well-documented as essential compounds contributing to strength development and microstructure densification in stabilized soils (Latifi, Horpibulsuk, et al., 2017b). New detection of Si (2.16%) and Al (0.88%) where is absent or minimal in other samples, pointing to enhanced pozzolanic

reactivity. The detection of Si and Al not only implies the involvement of SH-85's pozzolanic content but also indicates active participation of supplementary additives such as RP, which may offer reactive surfaces and promote hydration reactions. A more compact and aggregated microstructure, as seen under SEM, contrasting the loosely packed structure of untreated or solely SH-85-treated peat. These enhancements validate the synergistic effect of combining cement, RP, and SH-85, producing stronger, denser, and more mineralogically evolved structures through the formation of crystalline or semi-crystalline hydration phases. Such transformation is crucial for improving the engineering behaviour of problematic organic soils like peat.

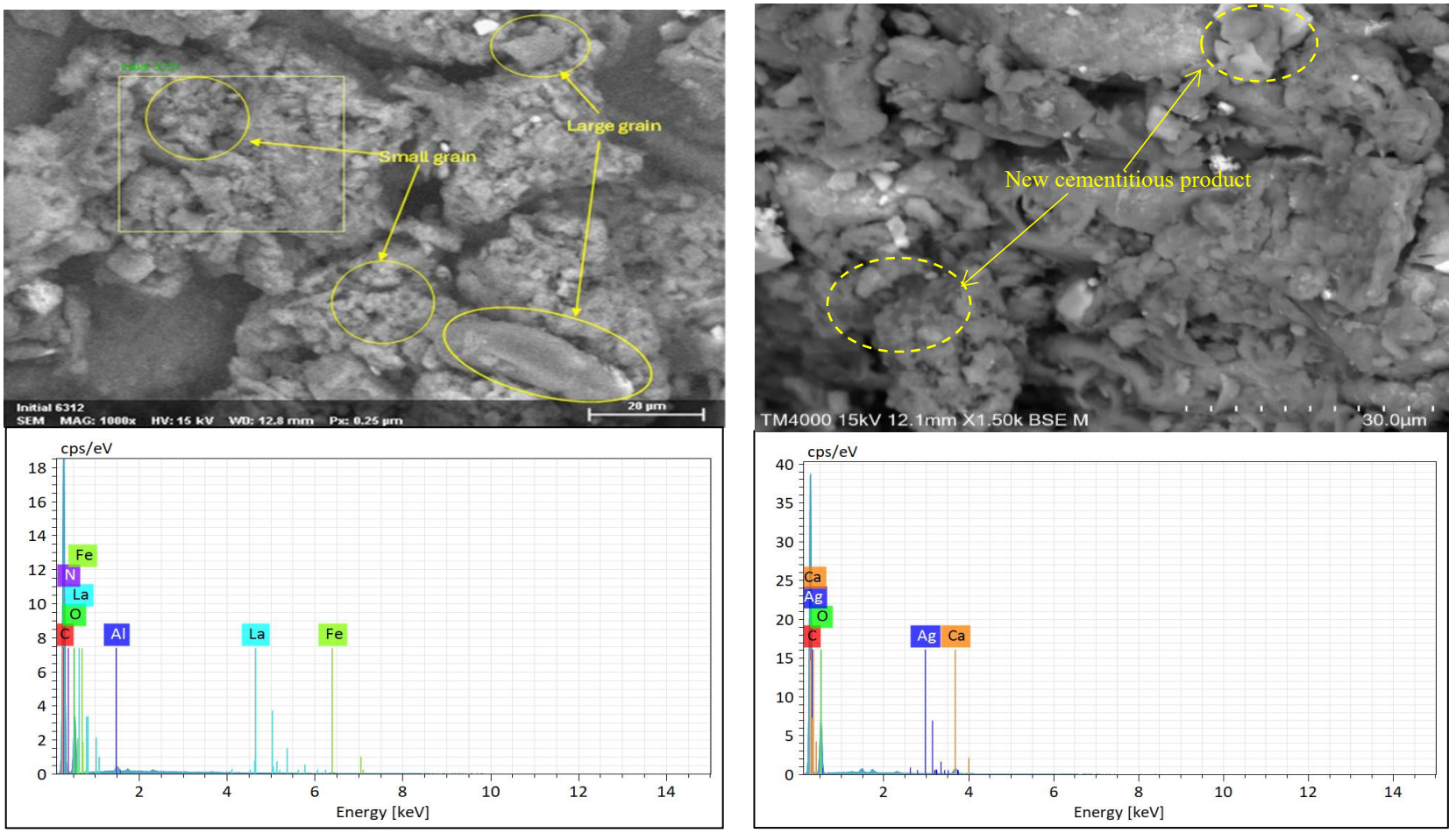
The scanning electron microscope (SEM) micrograph and energy-dispersive X-ray spectroscopy (EDS) analysis presented in Figure 4.22 compared the microstructural and elemental characteristics of peat soil treated with 5% cement, 15% rubber crumb (RC), and 6% SH-85 after 56 days of curing. This design mixture represents the highest strength compared to all samples. The SEM image reveals a substantially densified and consolidated matrix compared to other samples. The observed microstructure is characterized by aggregated particles, reduced pore voids, and tightly bonded surfaces, suggesting the presence of hydration products that have filled the interparticle spaces and contributed to the cohesion of the soil matrix. The EDX elemental spectrum further substantiates the formation of new mineralogical phases. The elemental analysis identifies the presence of calcium (Ca = 16.61%), oxygen (O = 29.17%), silicon (Si = 2.99%), and aluminum (Al = 1.04%). The results show key constituents of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) compounds. The co-existence of these elements in significant proportions confirms the occurrence of pozzolanic and cement hydration reactions. These reactions typically involve the interaction between calcium

hydroxide, produced from cement hydration, and the reactive silica and alumina present in SH-85 and the organic matrix of peat, resulting in the precipitation of C-S-H and C-A-H compounds. These cementitious products are essential for enhancing the mechanical integrity and durability of stabilized soils by improving particle bonding and reducing permeability. In addition to the major cementitious elements, a minor concentration of sulfur (S = 0.81%) was also detected. This finding suggests the possible formation of secondary sulfate-based mineral phases, such as ettringite, particularly when sufficient aluminum and calcium are present. Ettringite, although not explicitly confirmed through morphology in this analysis, is known to contribute to early-stage strength and volume stability in cementitious systems.

When compared to previous results, such as those from SH-85 only treated peat, which exhibited a calcium content of approximately 1.14% and lacked detectable silicon, the current sample demonstrates a significantly enhanced elemental profile conducive to hydration product formation. Similarly, in samples treated with cement and rubber powder (RP), the calcium content was reported at around 5.24%, with relatively lower silicon and aluminum levels. The combination of cement, RC, and SH-85 in the present mix design has resulted in a substantially richer reactive environment, producing a more chemically matured and physically integrated matrix. This supports the hypothesis that the synergistic effect of cement and SH-85, along with the physical properties of rubber crumb, collectively enhance both the chemical and structural stabilization of peat.

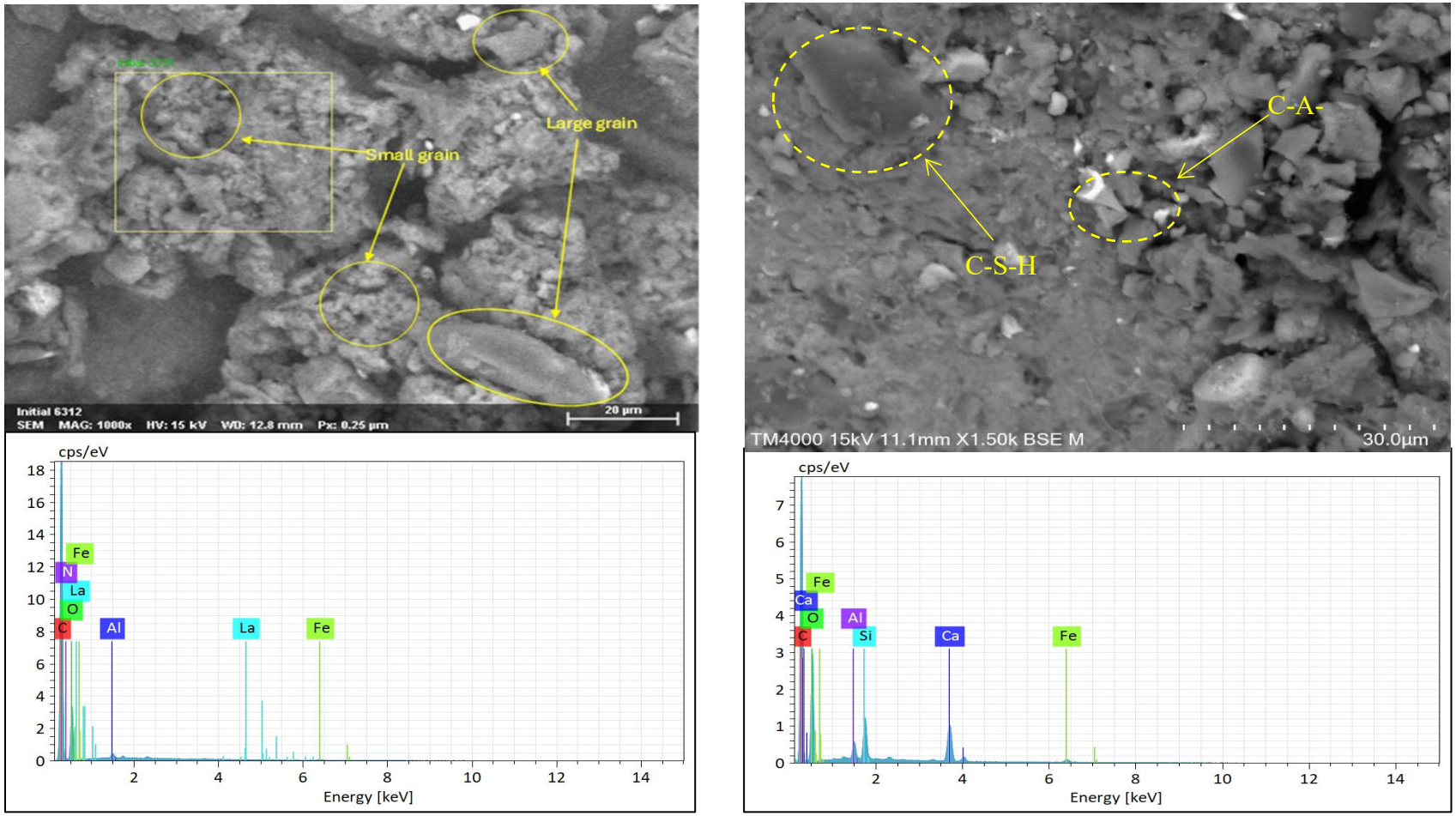
Therefore, the integrated SEM-EDX findings provide compelling evidence for the formation of new cementitious and mineralogical compounds in the stabilized peat. The presence of C-S-H and C-A-H, inferred from both morphological and elemental signatures,

validates the long-term pozzolanic and hydration activity occurring within the treated matrix of peat. This transformation is important in improving the load-bearing capacity, stiffness, and durability of the treated peat, confirming the efficacy of the selected treatment formulation for problematic peat soils.



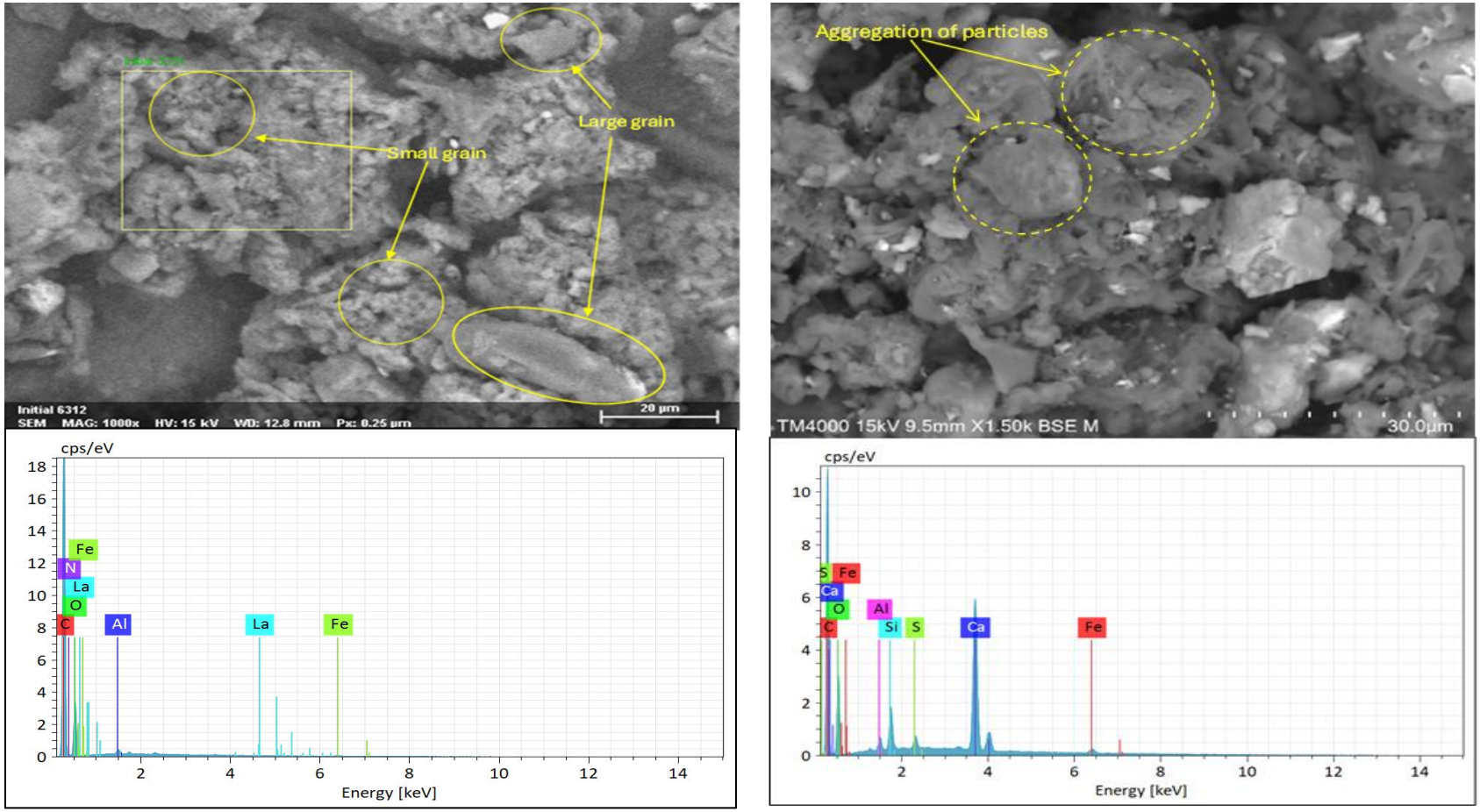
(a) Untreated peat (b) Treated peat (Pt+3%SH-85)

Figure 4.20: SEM image and EDX result of untreated peat and Pt+3%SH-85



(a) Untreated peat (b) Treated peat (Pt+5%C+5%RP+12%SH-85)

Figure 4.21: SEM image and EDX result of untreated peat and Pt+5%C+5%RP+12%SH-85



(a) Untreated peat

(b) Treated peat (Pt+5%C+15%RC+6%SH-85)

Figure 4.22: SEM image and EDX result of untreated peat and Pt+5%C+15%RC+6%SH85

Table 4.6 presents the elemental composition of untreated and chosen treated peat samples, obtained through Energy-Dispersive X-ray Spectroscopy (EDX) analysis after 56 days of curing. The specimens were analysed using a scanning electron microscope (SEM) operated at 15 kV and a magnification of 1000×. To ensure consistency and reliability data, the elemental quantification was performed at three randomly selected locations on each sample, as recommended by standard microanalysis protocols (Goldstein et al., 2017). The results are presented in elemental form (% by mass), and in oxide equivalents (e.g., CaO, SiO_2, Al_2O_3) as shown in Table 4.7.

Table 4.6: EDX-Derived Elemental Content of Peat Samples Before and After Stabilization

Specimen / **Element**	**Untreated peat**	**Pt+3%SH85**	**Pt+5%Cement + 5%RP+12SH85**	**Pt+5%Cement + 15%RC+6%SH85**
C	65.51	61.90	53.35	47.88
O	29.97	29.83	37.06	29.17
N	3.49	-	-	-
Si	-	4.10	2.16	2.99
Ca	-	2.19	5.24	16.61
Al	0.44	0.89	0.88	1.04
Fe	0.57	0.78	1.30	1.48
S	-	0.31	-	0.81
La	0.02	-	-	-

Footnote: C-carbon, O-oxygen. N-nitrogen, Si-silica, Ca-calcium, Al-aluminum, Fe-iron, S-sulfur, La-lanthanum

The analysed samples are including untreated peat, as well as peat stabilized with combinations of cement, SH-85, and recycled materials such as rubber powder (RP) and rubber crumb (RC). From the data, untreated peat shows a dominant carbon content of 65.51%, indicative of its high organic composition. This is accompanied by 29.97% oxygen, 3.49% nitrogen, and trace levels of aluminum (0.44%) and iron (0.57%). The absence of silicon and calcium confirms the lack of cementitious compounds in the native

matrix. These values are consistent with the known characteristics of sapric peat, which consists mainly of highly decomposed organic matter (B. B. K. Huat et al., 2005).

The selection of SH-85 as a stabilizer in this study is based on its multifunctional chemical composition and its emerging effectiveness in the stabilization of problematic soils, including organic-rich and highly compressible peat. Unlike traditional binders such as cement and lime, SH-85 is a non-traditional biomass silica-based additive that reacts chemically with both the organic and inorganic fractions of the soil to form stable cementitious compounds. It has been shown to significantly improve shear strength, reduce compressibility, and enhance soil microstructure, especially in peat and organic soils where traditional stabilizers may underperform due to high organic content and low pH environments (N. Hassan et al., 2019).

SH-85 works through pozzolanic reactions, promoting the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which bind soil particles and fill pore spaces. This leads to a denser matrix and a reduction in moisture sensitivity (Latifi et al., 2013). Upon treatment with 3% SH-85, the elemental profile of the treated peat changes moderately. Carbon content decreases to 61.9%, while silicon (Si = 4.10%) and calcium (Ca = 2.19%) are newly detected, indicating the onset of chemical interaction between the additive and the organic matrix. Aluminum (0.89%) and sulfur (0.31%) also appear, suggesting the presence of pozzolanic and potentially sulfate-based compounds. These changes reflect the early formation of hydration products, supporting the effectiveness of SH-85 in chemically modifying and reinforcing the peat structure (Barman & Dash, 2022).

The introduction of cement and recycled rubber powder (Pt+5%C+5%RP+12%SH-85) leads to further transformation. Carbon content reduces significantly to 53.35%, while oxygen increases to 37.06%, reflecting a higher proportion of mineral oxides and hydrated products. Notably, calcium increases to 5.24%, and the presence of silicon (2.16%) and aluminum (0.88%) supports the formation of pozzolanic reaction products such as C-S-H and C-A-H (Kazemian et al., 2011b). The incorporation of RP likely provides additional surface area for binding and contributes to densification, as observed in SEM micrographs.

The most chemically mature composition is observed in the sample treated with 5% cement, 15% rubber crumb, and 6% SH-85 (Pt+5%C+15%RC+6%SH-85). This specimen shows the lowest carbon content (47.88%) and the highest calcium concentration (16.61%), indicating extensive replacement of organic matter by cementitious phases. Silicon (2.99%), aluminum (1.04%), and sulfur (0.81%) are all present in substantial amounts. These findings are consistent with the extensive formation of C-S-H and C-A-H, as well as secondary sulfate-based compounds such as ettringite, which can form in the presence of sulfur and aluminum (Ahmad et al., 2023).

The progression from untreated to fully treated peat clearly shows a transition from an organically dominant matrix to a mineralogically complex, cementitious system. The elemental data strongly support the formation of binding phases that are crucial to the mechanical strength and durability of stabilized soils. This transformation is consistent with the established reaction mechanisms of cement and pozzolanic stabilization in organic soils (J. A. Rahman et al., 2016).

In geotechnical and materials engineering research, particularly when evaluating the effects of soil stabilization using chemical additives, it is common practice to convert

elemental composition data obtained from Energy Dispersive X-ray Spectroscopy (EDX) into oxide form. This approach aligns with cement chemistry principles and is widely accepted for interpreting the chemical behaviour of treated soils. Oxide-based reporting enables a more accurate assessment of pozzolanic activity and mineralogical changes that occur during the curing process. Therefore, all elemental results in this study were converted to their corresponding oxide forms for consistency and clarity.

The transformation of elemental data into oxide form is carried out by applying a stoichiometric conversion factor, which is based on the molecular mass ratio between the oxide and the respective element. This conversion allows researchers to estimate the theoretical oxide composition that would result if the elements reacted fully with oxygen, as typically occurs during cement hydration reactions. For example, to convert calcium (Ca) to calcium oxide (CaO), the molar mass of Ca is 40.08 g/mol, and the molar mass of CaO is 56.08 g/mol. The conversion factor is therefore calculated as:

$$\frac{\text{Molar Mass of CaO}}{\text{Molar Mass of Ca}} = \frac{56.08}{40.08} = 1.399 \qquad \text{Equation 4.1}$$

Applying this factor to an elemental calcium content of 16.61% (taking example of design mixture: Pt+5%C+15%RC+6%SH-85), the equivalent oxide form is determined using the following formula:

$$\text{CaO} = 16.61 \times 1.399 = 23.24 \qquad \text{Equation 4.2}$$

Thus, a calcium content of 16.61% corresponds to 23.24% CaO. This method was applied consistently to all major elements identified in the EDX analysis, including silicon (Si), aluminum (Al), iron (Fe), sulfur (S), and calcium (Ca). Table 4.7 below summarizes the conversion factors used in this study for transforming elemental content into oxide

equivalents while Table 4.8 represent the Oxide Composition of the untreated and treated peat specimens.

Table 4.7: Oxide Conversion Factors

Element	Oxide Form	Molar Mass of Element (g/mol)	Molar Mass of Oxide (g/mol)	Conversion Factor
Ca	CaO	40.08	56.08	1.399
Si	SiO_2	28.09	60.08	2.139
Al	Al_2O_3	26.98	101.96	1.889
Fe	Fe_2O_3	55.85	159.69	1.429
S	SO_3	32.06	80.06	2.497

Table 4.8: Converted Oxide Composition of the untreated and treated peat

Specimen	SiO_2	CaO	Al_2O_3	Fe_2O_3	SO_3
Untreated peat	-	-	0.83	0.81	-
Pt+3%SH-85	8.77	3.06	1.68	1.11	0.78
Pt+5%Cement+5%RP+12SH-85	4.62	7.33	1.66	1.86	-
Pt+5%Cement+15%RC+6%SH-85	6.4	23.24	1.96	2.11	2.03

The use of oxide forms in EDX results provides a more meaningful interpretation of the mineralogical and cementitious behaviour of treated peat soils. For instance, increases in CaO and SiO_2 content are typically indicative of the formation of calcium silicate hydrate (C-S-H) gels, while higher Al_2O_3 values may correspond with the development of calcium aluminate hydrate (C-A-H) or ettringite. These cementitious products play a critical role in enhancing the mechanical properties and durability of stabilized soils. Therefore, the analysis of oxide-based data is essential for linking chemical composition to the physical and mechanical behaviour observed in laboratory testing. In this study, converted oxide values were used to compare the chemical evolution of untreated and treated peat samples. The oxide-based analysis also served as supporting

evidence for microstructural changes observed in SEM images and explained the strength development patterns revealed by unconfined compressive strength (UCS) and California bearing ratio (CBR) tests.

4.7 Summary

This chapter has presented and discussed the experimental findings from the laboratory investigation into the stabilization of peat using scrap tire materials in combination with cement and SH-85. The results have been systematically analyzed to address the research objectives and provide insight into the performance of the treated peat in comparison to the untreated material.

The physical and index properties of the untreated peat confirmed its highly challenging nature for construction, with extremely high moisture content, high organic matter, low pH, and low specific gravity. These characteristics underscored the necessity for stabilization interventions. Upon treatment, noticeable improvements in pH, compaction characteristics, and consistency limits were observed, indicating enhanced soil workability and reactivity with the stabilizers.

Mechanical testing, particularly UCS and CBR, demonstrated significant strength gains with the inclusion of cement, SH-85, and rubber additives. The optimum mix design was identified based on peak UCS and CBR values, showing that an appropriate balance of cement content, SH-85 dosage, and rubber percentage can yield substantial performance improvements. Strength gains were also correlated with curing time, highlighting the progressive nature of pozzolanic and cementitious reactions.

Failure mode analysis of UCS specimens revealed a transition from brittle shear in untreated peat to more ductile and cohesive failures in treated samples, reflecting improved bonding and load distribution. CBR results further validated the suitability of the optimized mix for subgrade applications, meeting or exceeding standard requirements for road construction in peat areas.

Microstructural analysis through SEM and EDX provided visual and chemical evidence of the stabilization mechanisms. SEM images showed a denser, more cemented matrix with reduced voids, while EDX analysis confirmed the presence of key elements such as calcium and silicon, indicating the formation of cementitious products like calcium silicate hydrates (C-S-H). These microstructural improvements directly supported the observed mechanical enhancements.

In conclusion, the findings from this chapter clearly demonstrate that the integration of scrap tire materials with cement and SH-85 significantly improves the engineering properties of peat. The optimal mix achieved notable strength increases, improved bearing capacity, and microstructural densification, making it suitable for subgrade applications. These results form a strong foundation for the numerical modelling work presented in the next chapter, where the real-world performance of the optimized mix will be evaluated under simulated embankment loading conditions.

CHAPTER 5

MODELLING OF THE REINFORCED SOIL BY GEOSTUDIO APPLICATION

5.1 Overview

In geotechnical research, numerical modelling serves as a robust tool for simulating the stress-strain behaviour of soil systems under varying loading conditions, particularly in complex subsoil environments such as tropical peat. Unlike empirical consultancy-based design, which typically prioritizes constructability, this chapter contributes scientifically by integrating experimentally validated material parameters into a finite element modelling (FEM) framework. The simulations were executed using SIGMA/W and SLOPE/W, a module within the GeoStudio suite were chosen for their capacity to model coupled stress-deformation and slope stability behaviour in variably saturated and highly compressible soils (Geo-Slope International, 2019).

The constitutive models employed in this study which is Mohr-Coulomb and Modified Cam Clay (MCC) were selected to simulate both the frictional behaviour and volumetric compression of the stabilized sapric peat. These models were calibrated using laboratory results derived from an optimized mix formulation comprising peat+5% cement+15%rubber crumb+6% SH85, as established in Chapter 4. The integration of these stabilized parameters into numerical simulations represents a key research novelty, addressing the knowledge gap in modelling the long-term settlement and load-bearing performance of chemically stabilized tropical peat soils.

The modelling framework was further aligned with the Guidelines for Construction on Peat and Organic Soils in Malaysia Construction Research Institute of Malaysia (CREAM) (2019), which provided benchmark values for consolidation duration, geometric assumptions, and layer configurations. Additionally, site-specific parameters from Kg Endap, Kota Samarahan were incorporated to improve the accuracy and applicability of the model, enhancing its relevance for Sarawak-specific engineering practices.

This chapter does not merely apply existing software tools but advances the field by demonstrating how hybrid stabilizers influence constitutive soil behaviour when translated from laboratory scale to field-scale numerical simulations. Such an approach provides predictive insights into settlement performance, improving design reliability for infrastructure development on marginal lands.

5.2 Numerical Modelling of Embankment Stability on Stabilized Peat Soil

This chapter presents a scientifically grounded investigation into the stability of embankments constructed over chemically stabilized peat, with a focus on predictive modelling using the finite element method (FEM) in GeoStudio 2022. Rather than offering a general design or consultancy-based evaluation, the purpose of this chapter is to critically examine the performance of a novel stabilization mixture (5% OPC, 15% rubber crumb, and 6% SH-85) under controlled loading conditions, and to explore its implications on long-term settlement and slope stability.

By adopting both SIGMA/W for stress-deformation and consolidation analysis and SLOPE/W for slope stability modelling, this study provides an integrated framework for assessing the geotechnical response of stabilized peat subgrades. The modelling strategy was specifically aligned with the third objective of this research which is to evaluate how

the optimum reinforced mixture performs under embankment loading, using empirical inputs derived from rigorous laboratory testing. Unlike conventional design studies, this simulation is embedded in a research context, calibrated with locally sourced Sarawak peat parameters, and benchmarked against national standards from Construction Research Institute of Malaysia (CREAM), 2019.

In the modelling structure, only half of the embankment cross-section was modelled due to its symmetry about the centreline. The modelled domain includes a 2-meter-high embankment with a 1V:2H side slope, underlain by a 5-meter-thick peat layer, of which the upper 0.3-0.5 meters was stabilized. Beneath the peat lies a 15-meter thick, soft clay layer modelled using the Modified Cam Clay (MCC) model. The model extends 40 meters horizontally to capture potential failure mechanisms beyond the embankment toe as can be seen in Figure 5.2.

To simulate realistic loading conditions, a 10 kPa surcharge was applied to the embankment crest, representing the pavement pressure for a low-volume road. The staged construction procedure followed the Guidelines for Construction on Peat and Organic Soils in Malaysia (CREAM, 2019), with the embankment constructed in four 0.5 m lifts. This phasing was employed to control excess pore water pressure and prevent undrained shear failure in the underlying soft soil layers. The simulation aimed to meet the performance target of 90% primary consolidation or ≤500 mm total settlement within six months and ensure that post-construction settlement did not exceed 200 mm over a three-year monitoring period. These criteria reflect both structural serviceability and long-term functionality.

Accurate finite element modelling depends heavily on realistic input parameters representing the hydro-mechanical behaviour of the subsurface strata. Key parameters adopted include saturated unit weight (γ_{sat}), initial void ratio (e_0), effective friction angle (φ'), Poisson's ratio (ν), elastic modulus (E_s), and hydraulic conductivity (K_x), and the constitutive parameters for the Modified Cam Clay (MCC) model, specifically the compression index (λ), swelling index (κ), and overconsolidation ratio (OCR). Due to the heterogeneity, high organic content, and amorphous microstructure of tropical sapric peat, it is imperative to use parameter values that are regionally calibrated and validated against field and laboratory data from Sarawak. This ensures that the modelling outputs remain both realistic and representative of actual ground conditions, particularly in the study area of Kg Endap, Kota Samarahan.

Parameter values were calibrated using laboratory test results and validated against regional data specific to tropical peat soils in Sarawak. For untreated peat, the adopted parameters were γ_{sat} = 12 kN/m³, e_0 = 3.49, φ' = 20°, ν = 0.38, and Es = 840 kPa. These values were integrated from laboratory testing and are supported by regional geotechnical investigations and laboratory tests on Sarawak peat, which is typically characterized by extremely high natural moisture content, low shear strength, and significant compressibility. The low values of γ_{sat} and E_s reflect the poor load-bearing capacity and high deformability of the natural peat, which poses serious challenges in infrastructure development. These values correspond with earlier studies by Kolay et al. (2010) that highlighting the high compressibility and low strength of sapric peat.

For stabilized peat, the model incorporated γ_{sat} = 15 kN/m³, e_0 = 1.24, φ' = 25°, ν = 0.38, and E_s = 3850 kPa. The significant improvement in stiffness and strength, along with

the reduction in void ratio, is attributed to the combined effects of cement hydration products that bind the organic particles, and the reinforcing properties of rubber crumb and SH-85. This stabilization system improves the ductility of the stabilized matrix and reduces brittleness, thereby enhancing the material's load-bearing performance. The enhancement in stiffness and reduction in void ratio was attributed to cementitious bonding and rubber reinforcement effects. These values are consistent with Ahmad et al. (2023), who reported similar improvements in stabilized organic soils.

The underlying soft clay layer was modelled using the MCC model with $\lambda = 0.2$, $\kappa = 0.04$, $\varphi' = 25°$ and OCR = 1.2. These were derived from prior MCC-based studies of Sarawak soft clays (K. N. Prasad et al., 2013), who validated the applicability of MCC modelling in predicting settlement and strength evolution in tropical organic soils. A constant hydraulic conductivity of $K_x = 0.004$ m/day was applied across the peat and clay layers, based on laboratory results from B. B. K. Huat et al. (2005), and reflecting the low permeability of treated peat.

The Modified Cam Clay (MCC) model was chosen for soft clay and peat layers due to its ability to simulate time-dependent volumetric strain and pore-pressure evolution under variable mean effective stress and deviatoric stress; a phenomena that are particularly dominant in organic and highly compressible soils (Tan & Othman, 2014; Hashim & Islam, 2008). Critical parameters such as the compression index (λ), swelling index (κ), Poisson's ratio (ν), and effective friction angle (φ') were integrated from laboratory testing. These parameters were used to calibrate the constitutive behaviour of stabilized and untreated materials, as shown in Table 5.1.

In instances where elastic modulus values were not directly measurable, such as in certain MCC-based simulations of stabilized peat and soft clay, calibration was performed using sensitivity and back-analysis methods from oedometer test data. This approach is supported by Tamrakar et al. (2018), who established its reliability for time-dependent soils. The alignment of input parameters with established regional studies (Sakr et al., 2022; Sheng et al., 2013; Srijan et al., 2024; Zainorabidin & Wijeyesekera, 2007a) ensures that the model is adaptable, contextually accurate, and scientifically defensible for engineering applications in Kg Endap.

In this study, stability evaluation was performed using the Morgenstern-Price method in SLOPE/W. This technique is suitable for complex, layered systems and satisfies both force and moment equilibrium (Morgenstern & Price, 1968; Das, 2013). Factor of Safety (FoS) values were calculated for various stabilization thicknesses. Multiple models were tested with varying stabilized peat thicknesses to determine optimal layer depth and performance reliability.

This approach highlights a key scientific contribution; the integration of material-specific laboratory results into calibrated numerical simulations under real-world boundary conditions and loading schemes. The resulting analyses support informed design decisions and contribute to a deeper understanding of soft soil-structure interaction in tropical peat environments.

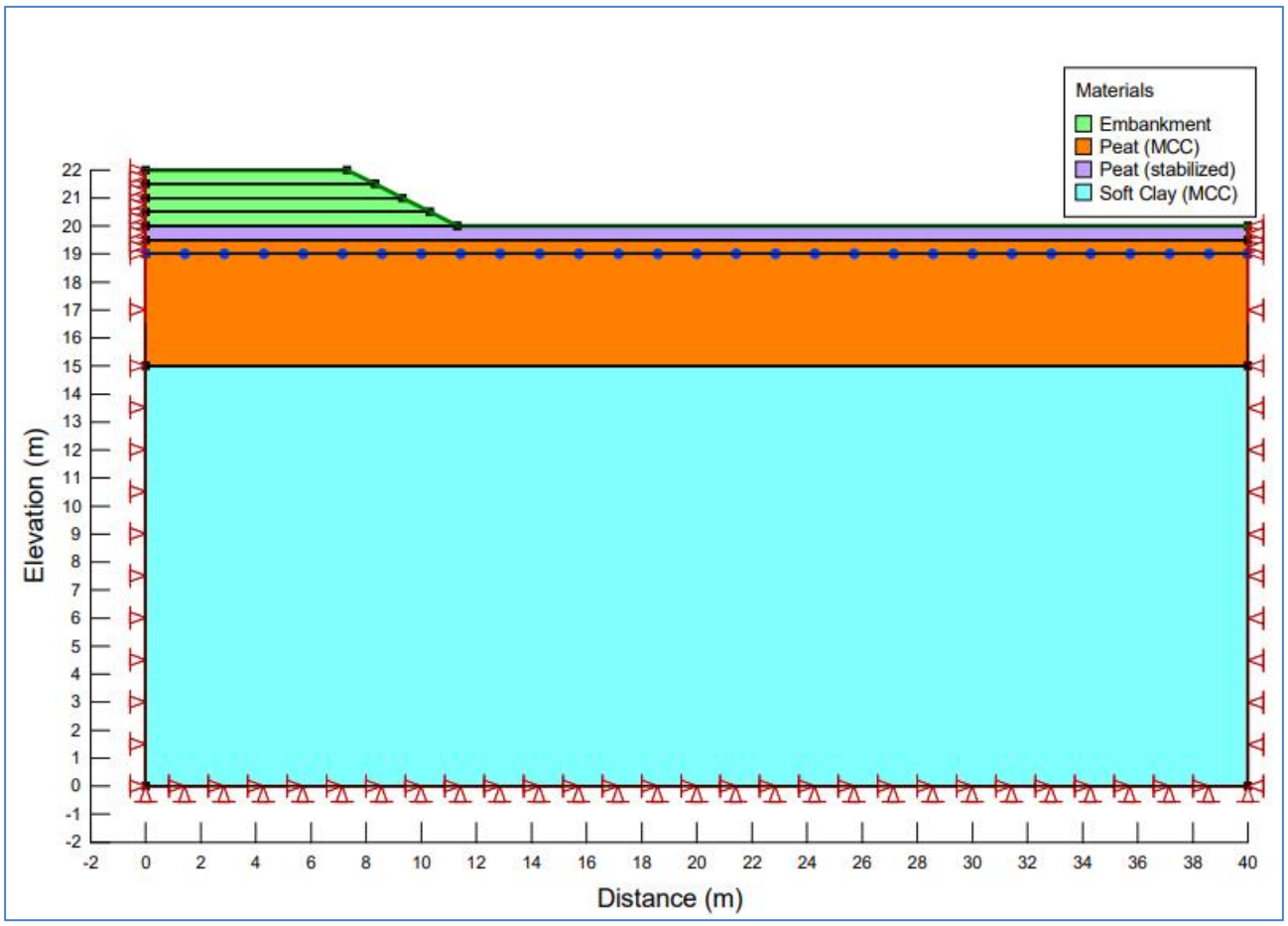


Figure 5.2: Soil profile of studied embankment

Table 5.1: Materials Properties Used in the Numerical Analysis

Soil Type	Constitutive Model	γsat (kN/m³)	e_0	OC Ratio	λ	κ	φ' (°)	ν	E_s (kPa)	Kx (m/d)	Reference
Embankment	Mohr-Coulomb	19	1.5	–	–	–	30	0.35	10000	0.004	(Sakr et al., 2022) (Srijan et al., 2024)
Clay	Mohr-Coulomb	16	1.5	–	–	–	25	0.38	2000	0.004	(GeoStudio, 2022) (CREAM, 2019) (Sakr et al., 2022)
Peat (untreated)	Mohr-Coulomb	12	3.49	–	–	–	20	0.38	840	0.004	From the study (B. B. K. Huat, 2004) (Zainorabidin & Wijeyesekera, 2007a)
Peat (stabilized)	Mohr-Coulomb	15	1.24	–	–	–	25	0.38	3850	0.004	From the study (B. B. K. Huat, 2004)
Soft Clay	MCC	16	1.5	1.2	0.2	0.04	25	0.36	–	0.004	(GeoStudio, 2022) (CREAM, 2019) (B. B. K. Huat, 2004) (Sakr et al., 2022)
Peat (MCC)	MCC	12	1.5	1.2	0.2	0.05	25	0.38	–	0.004	(CREAM, 2019) (Sheng et al., 2013)

Note: MCC – Modified Cam Clay

5.3 Numerical Prediction of Settlement and Stability for Stabilized Peat Embankments

This section presents the results of settlement and stability analyses for embankments constructed over stabilized sapric peat, as predicted using finite element simulations in SIGMA/W and SLOPE/W (GeoStudio 2022). The modelling framework integrates experimental parameters obtained from laboratory testing of the optimized stabilization mix (5% cement, 15% rubber crumb, and 6% SH-85), thus enhancing the representativeness and scientific validity of the simulation outcomes.

5.3.1 Predicted Settlement Behaviour

The time-dependent settlement behaviour of embankments constructed on stabilized peat was numerically simulated using SIGMA/W, part of the GeoStudio 2022 software application. This section presents a detailed analysis of the modelled vertical deformation curves for two design scenarios involving 300 mm and 500 mm thick stabilized peat layers. The modelling was carried out to directly address the third objective of the study, namely, to analyse the settlement performance of the optimum design mixture for the stabilized sub-grade layer. The results were evaluated at three critical time intervals: six months corresponding to the surcharge period, thirty-six months representing three years of post-construction, and eighty-four months representing seven years of long-term performance. These intervals were compared against the regulatory thresholds established in the Guidelines for Construction on Peat and Organic Soils in Malaysia (CREAM, 2019), which specify acceptable settlement limits of less than 500 mm at six months, less than 200 mm of additional settlement within three years, and less than 400 mm of additional settlement within seven years beyond the preceding interval.

For untreated peat, the model predicted a settlement of approximately 536 mm within the initial 6-month surcharge period (Figures 5.3a and 5.4a). Settlement continued slightly over the subsequent 3-year post-construction monitoring period, reaching 546 mm, with additional displacement by year seven at 559mm. This large deformation exceeds the acceptable limit of 500 mm, confirming the well-documented high compressibility and long-term deformation of natural sapric peat (Kalantari & Huat, 2008; M. Sa'don et al., 2016). The analysis of untreated peat indicated that the settlement at six months was approximately 536 mm, which exceeded the acceptable limit of 500 mm. This clearly demonstrates that untreated sapric peat is incapable of meeting the required engineering standards due to its high compressibility and low shear strength. At three years, the settlement had increased to 546 mm, and by seven years the settlement occurs another 13mm which is at 559 mm. Although the incremental settlements between the six-month, three-year, and seven-year intervals technically met the incremental limits, the initial failure to satisfy the six-month criterion rendered untreated peat unsuitable for embankment foundations. This observation is consistent with the literature, which highlights the extremely high settlement potential of Sarawak peat and its inability to sustain loads without treatment (Kalantari & Huat, 2008; M. Sa'don et al., 2016).

The introduction of a 300 mm stabilized layer significantly improved performance. The settlement after six months was approximately 386 mm, well within the 500 mm target. After three years, the settlement increased to 411 mm, indicating an incremental settlement of 25 mm beyond the surcharge period. This value was far below the 200 mm allowance specified for three years, showing that the stabilized layer effectively minimized secondary compression. At seven years, settlement was measured at 412 mm, corresponding to only 1 mm of additional deformation compared to the three-year value. This negligible increase

demonstrates that the primary consolidation had largely completed within the initial surcharge period and that long-term creep was almost entirely suppressed. The stability of the settlement curve over the long term highlights the effectiveness of stabilization in enhancing stiffness and reducing void ratio, thereby improving load-bearing capacity as stated in study by N. Hassan et al. (2019). Similarly, the 500 mm stabilized layer showed comparable results. Settlement after six months was recorded at 389 mm, which was also within the 500 mm target. At three years, the settlement had reached 414 mm, representing an additional 25 mm, once again well below the 200 mm threshold. By seven years, the settlement remained at 414 mm, indicating that no significant long-term deformation had occurred. The similarity between the 300 mm and 500 mm stabilization cases suggests that increasing the stabilized thickness does not produce proportionally greater benefits in terms of long-term settlement resistance. This supports the argument that 300 mm represents an optimum thickness for stabilization in terms of both performance and material efficiency.

The mechanisms responsible for settlement reduction in stabilized peat include the densification of the soil matrix through reduced void ratio, the formation of cementitious compounds that bond soil particles, and the resulting increase in effective stiffness and cohesion. These changes can reduce the capacity of the stabilized soil to undergo large-scale consolidation. Furthermore, as discussed by N. Hassan et al. (2019), the pozzolanic reaction between SH-85 and cementitious compounds produces additional calcium silicate hydrate (C-S-H), which fill pore spaces and bind organic particles together that contributes to early strength development and deformation control. Previous studies by Duraisamy et al. (2007) and Kazemian et al. (2011a) support these findings, showing that chemical stabilization with cementitious and pozzolanic additives significantly reduces

compressibility and increases the stiffness of peat soils, leading to marked reductions in settlement. The scientific rationale behind these results is consistent with the literature on stabilized organic soils. As shown by Ibrahim et al. (2014) and Kalantari & Huat (2008), the application of cementitious and polymeric stabilizers such as SH-85 enhances the interparticle bonding, reduces void ratio that is resulting in elevated shear strength while supporting faster site readiness for construction activities.

The result from the stabilization process is a soil structure that resists primary settlement more effectively and suppresses secondary compression almost entirely. This explanation is consistent with both experimental and numerical studies that demonstrate the positive effects of chemical stabilization on peat soil behaviour (Duraisamy et al., 2009; Kalantari, 2019). By integrating the settlement results with the objectives of the study, it can be concluded that the characterization of stabilized sapric peat through laboratory testing and microstructural analysis using SEM and EDX provides the scientific foundation for understanding the improvements in mechanical performance. The settlement analysis conducted with GeoStudio confirms that these improvements translate into substantial reductions in both short-term and long-term deformation.

The evidence shows that the optimum design mixture applied at a 300 mm thickness is sufficient to meet regulatory targets and provide durable stability, making it the most practical and cost-effective solution for embankment construction on Sarawak peatlands. This diminishing return is consistent with prior findings by Kalantari and Huat (2008), who observed that stabilization beyond a critical depth often contributes minimally to bearing capacity when the most compressible surface layers are already treated.

In summary, untreated sapric peat fails to meet engineering requirements due to excessive settlement within the surcharge period, while stabilized peat, whether treated at 300 mm or 500 mm thickness, consistently meets or exceeds regulatory performance thresholds over six months, three years, and seven years. The comparable performance of the two stabilization thicknesses suggests that 300 mm is the optimum depth, providing substantial settlement reduction, long-term stability, and efficient use of resources. These findings contribute to the advancement of knowledge on peat soil stabilization and offer practical guidance for sustainable infrastructure development in tropical peat environments.

5.3.2 Stability Performance under Varying Stabilization Thickness

The stability of embankments constructed on untreated and stabilized sapric peat was evaluated using SLOPE/W with the Morgenstern–Price method, which satisfies both force and moment equilibrium and is considered appropriate for layered soil profiles and complex slip surface geometries (Morgenstern & Price, 1965). The objective was to connect the geotechnical response of the subgrade with the third aim of this research, namely, to analyse the settlement and stability performance of the optimum design mixture for the stabilized sub-grade layer using GeoStudio analysis. Figures 5.5 and 5.6 illustrate the computed slip surfaces and corresponding Factors of Safety (FoS) for embankments on untreated peat, 300 mm stabilized peat, and 500 mm stabilized peat.

For the untreated peat condition, the FoS was computed as 0.950, which is substantially lower than the minimum regulatory requirement of 1.3 stipulated by the Guidelines for Construction on Peat and Organic Soils in Malaysia (CREAM, 2019). This result indicates that untreated sapric peat is not only highly compressible, as demonstrated by the settlement analyses, but also critically unstable under embankment loading. The

shallow slip surface observed in the untreated case corresponds to the weak fibrous organic matrix, high moisture content, and very low shear strength of the natural deposit, confirming findings from earlier studies from Kazemian (2012) and M. Sa'don et al. (2016) that identified untreated peat as unsuitable for load-bearing structures. When the stabilized thickness was increased to 500 mm, the FoS improved only marginally to 1.588. This negligible increase compared to the 300 mm case suggests that beyond a certain depth, the additional treated thickness yields diminishing returns in stability performance. The upper 300 mm of sapric peat is recognized as the most active and compressible zone, and once this portion has been stabilized, additional treatment depth contributes little to further stability improvement (Kalantari & Huat, 2008). The similarity between the 300 mm and 500 mm FoS values supports the conclusion that 300 mm represents the optimum design thickness for balancing safety and material efficiency.

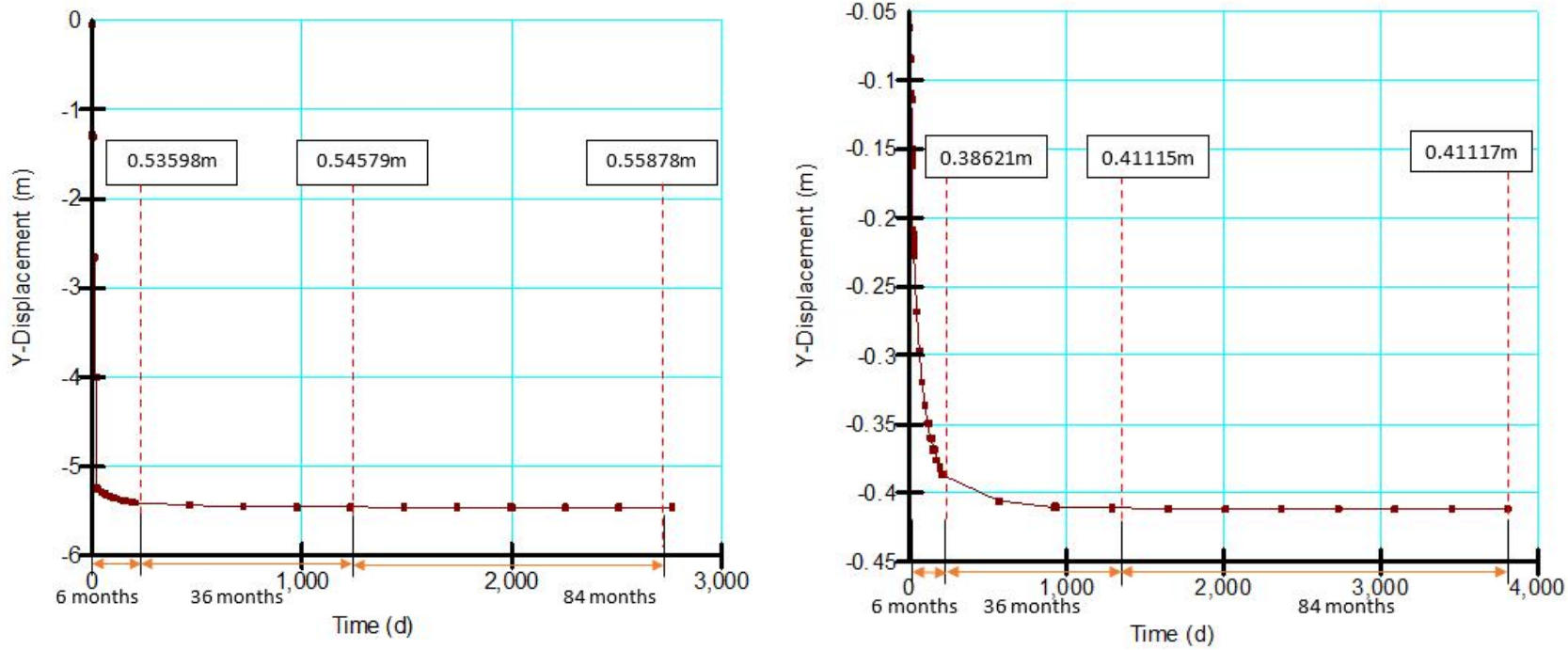
The improved stability observed in the stabilized cases is consistent with morphological evidence from SEM and EDX analyses presented earlier in this thesis, which showed denser particle arrangements, enhanced interparticle bonding, and the presence of cementitious products. These microstructural changes underpin the macroscopic performance improvements in both settlement reduction and slope stability, thereby linking the first two research objectives to the third. As stabilization altered both the physical properties such as reduced void ratio and higher UCS values; and the morphological features such as formation of cementitious bonds, the embankment performance in terms of deformation and stability was correspondingly enhanced. This behaviour is supported by the significant increase in stiffness and reduction in void ratio achieved through hybrid stabilization using cement, rubber crumb, and SH-85. These additives have shown to form durable cementitious products such as calcium silicate

hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which contribute to long-term strength and dimensional stability (N. Hassan et al., 2019; Latifi, Horpibulsuk, et al., 2017a).

The near-identical performance between the 300 mm and 500 mm stabilization scenarios demonstrates that a 300 mm treatment depth is sufficient to satisfy both settlement and stability requirements outlined by CREAM (2019). This finding is consistent with prior work demonstrating that stabilization of the uppermost peat layer is often adequate for improving both compressibility and strength (Sii, 2012; Sing et al., 2008). Furthermore, the plateauing of performance improvements beyond 300 mm treatment depth reinforces the importance of optimizing stabilization strategies to ensure economic efficiency without compromising safety. Moreover, similar studies by (Kalantari & Huat, 2008) have reported negligible settlement changes beyond the primary consolidation phase when peat is chemically treated with durable binders. While the three-year timeframe aligns with national design guidelines (CREAM, 2019), future research is encouraged to include long-term field monitoring or extended simulation durations (e.g., up to 10 years) to capture potential effects of environmental degradation or delayed secondary compression.

In summary, untreated sapric peat results in critically unstable embankments with FoS values below unity, confirming its unsuitability for infrastructure support. Stabilization using a hybrid mixture at 300 mm thickness enhances the FoS to 1.579, surpassing the regulatory safety threshold, while further increasing the thickness to 500 mm provides no meaningful additional benefit. These results confirm that stabilization directly addresses the research objectives by demonstrating that the optimum design

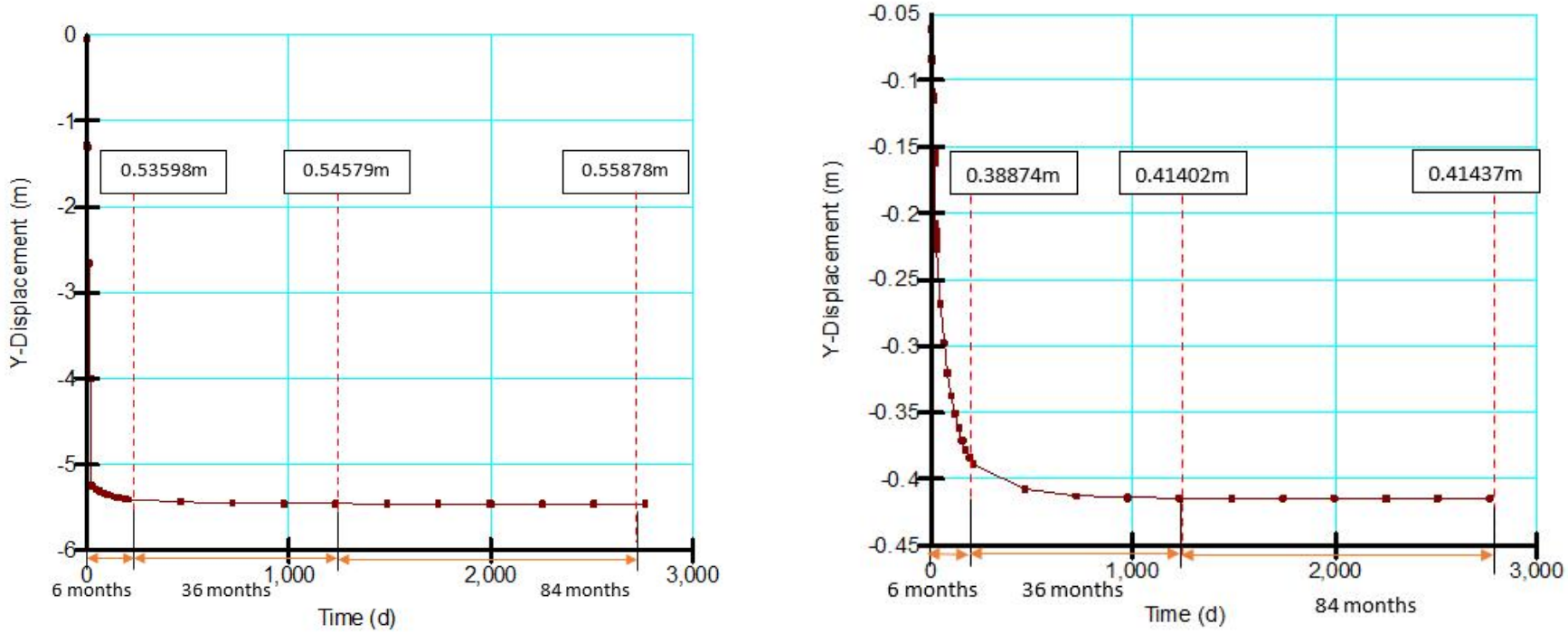
mixture, when applied at a practical depth, provides both settlement control and slope stability, making it a scientifically justified and economically efficient solution for infrastructure development on tropical peat.



a) Untreated peat

b) 300mm stabilized peat

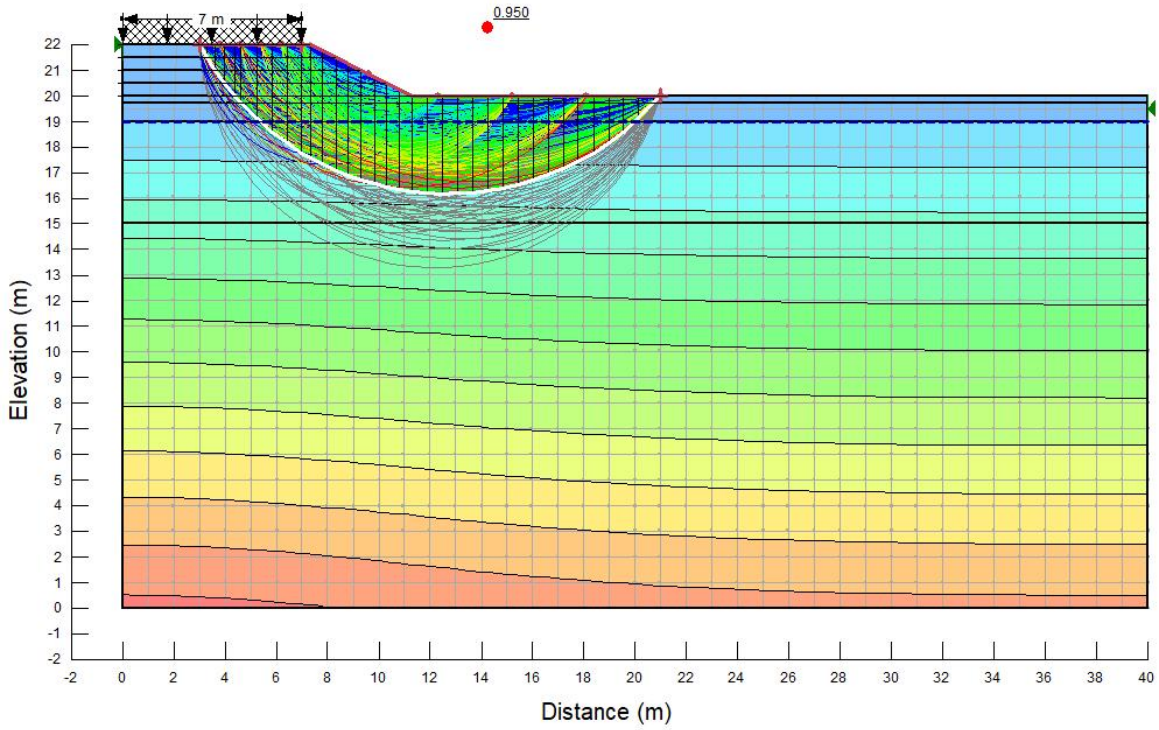
Figure 5.3: Settlement of untreated peat and 300mm stabilized peat for 6 months surcharge period, 3 years post construction and 7 years post construction



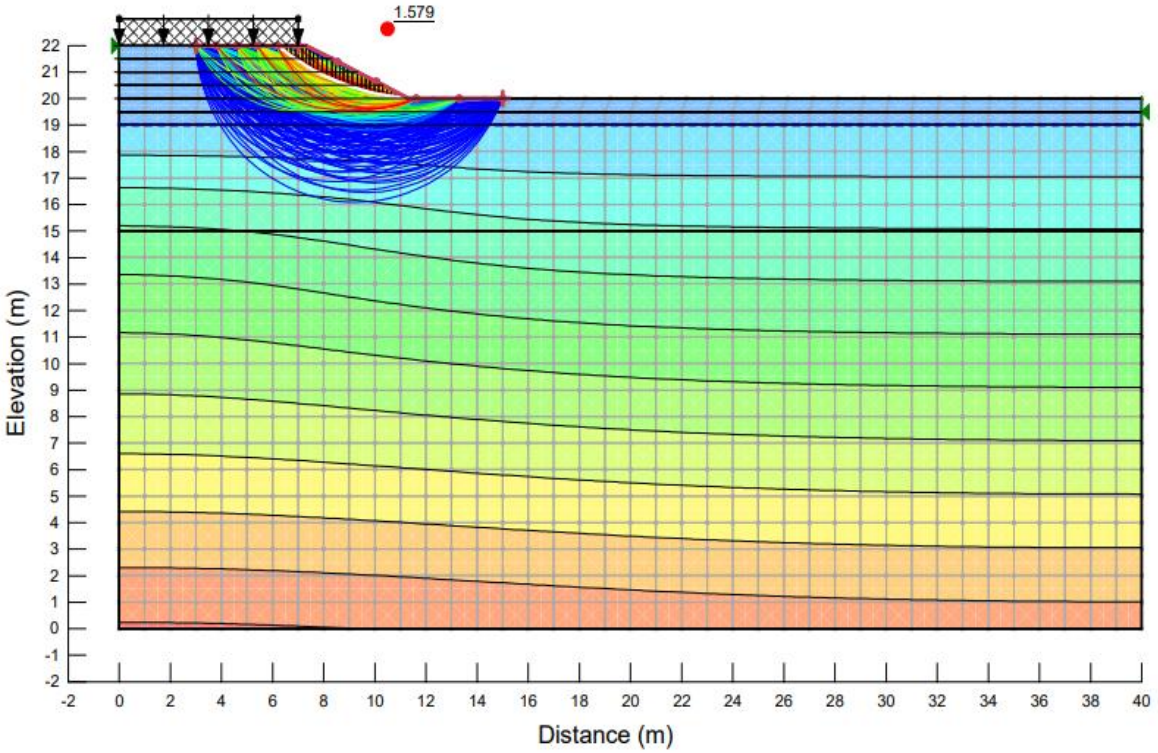
a) Untreated peat

b) 500mm stabilized peat

Figure 5.4: Settlement of untreated peat and 500mm stabilized peat for 6 months surcharge period, 3 years post construction and 7 years post construction

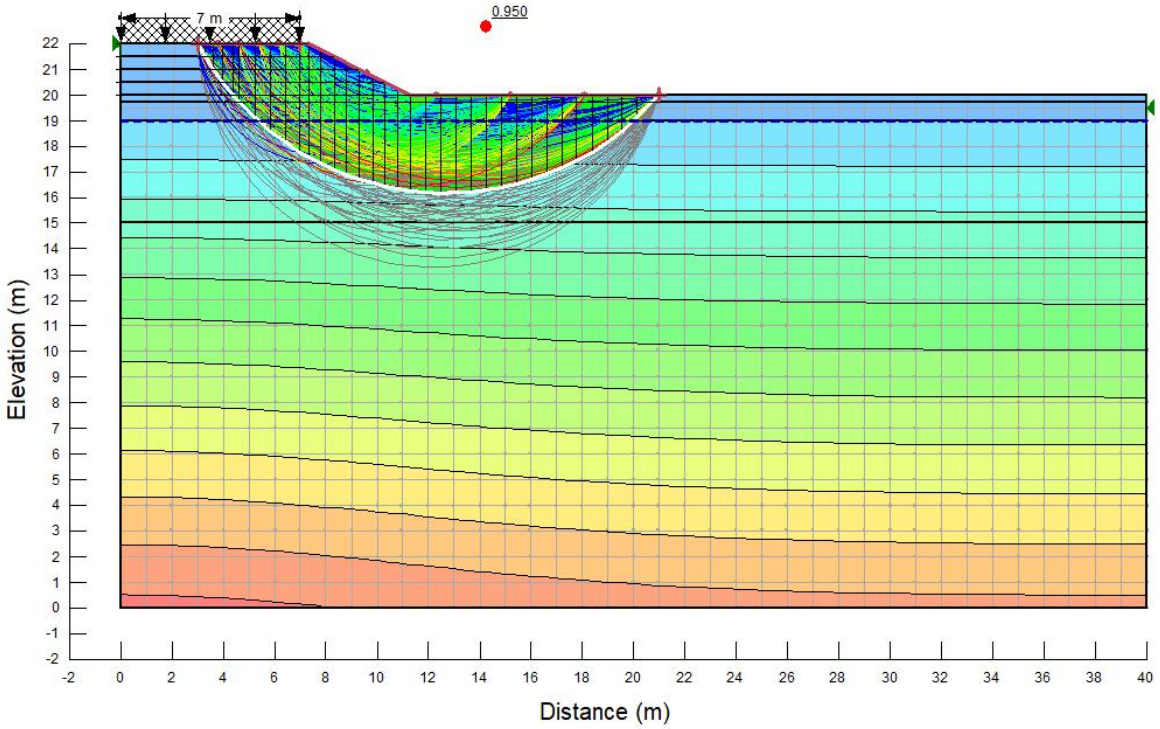


a) Untreated peat

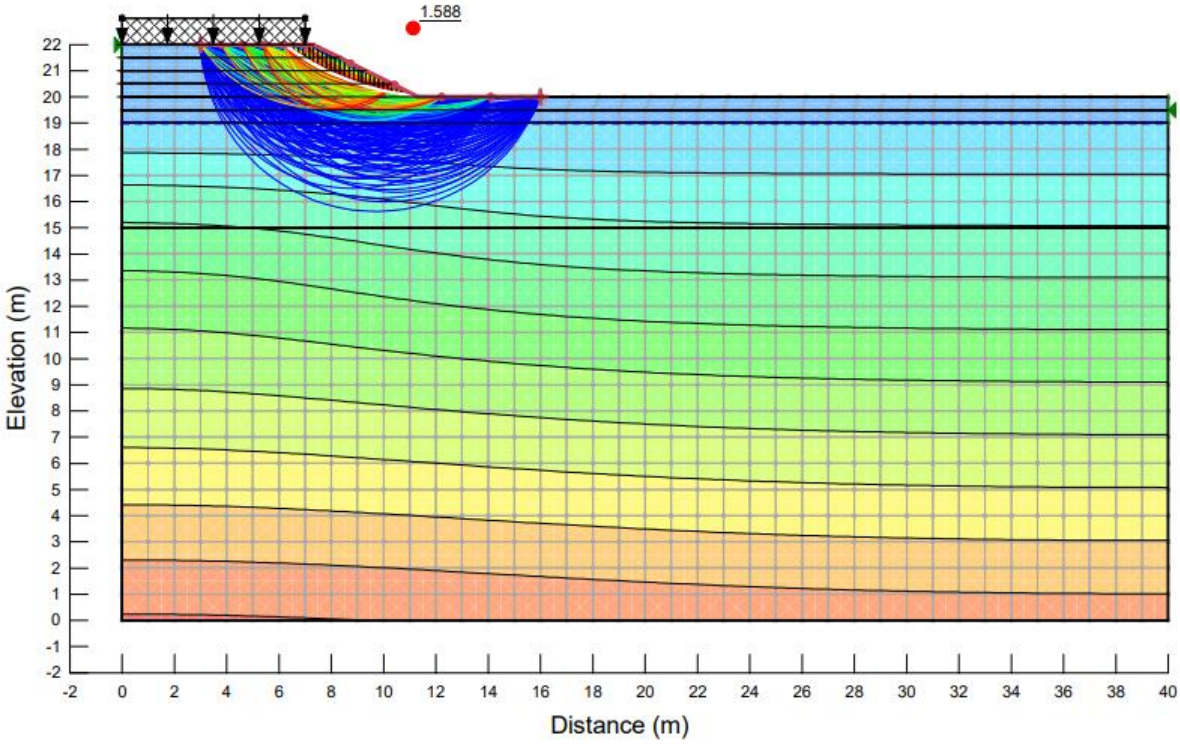


b) 300mm stabilized peat

Figure 5.5: Stability analysis for the untreated and stabilized peat of 300mm



a) Untreated peat



b) 500mm stabilized peat

Figure 5.6: Stability analysis for the stabilized peat of 500mm thickness

5.4 Summary

This chapter has presented the outcomes of the numerical modelling undertaken using GeoStudio's SIGMA/W and SLOPE/W modules to evaluate the settlement and stability performance of untreated and stabilized peat under embankment loading. The simulations were developed using material properties derived from laboratory testing, ensuring that the models reflected realistic conditions.

The modelling results clearly indicated that untreated peat exhibited excessive settlement and low stability, falling below acceptable performance thresholds. In contrast, embankments constructed on peat stabilized with the optimal mix (peat + cement + SH-85 + rubber additives) demonstrated substantial improvements in both settlement reduction and factor of safety. The application of thicker stabilized layers (500 mm) further enhanced performance, reducing settlement to within the CREAM limit of 200 mm and significantly increasing slope stability. Comparative analysis of the Mohr-Coulomb and Modified Cam Clay constitutive models provided insights into material behaviour, with the MCC model capturing the compressibility characteristics of peat more accurately. Deformation contour plots and slip surface analyses reinforced the laboratory findings, confirming that stabilization improved stiffness, reduced compressibility, and enhanced shear strength.

Overall, the numerical modelling validated the laboratory results from Chapter 4, demonstrating that the optimized stabilization approach is effective for field-scale applications. These findings provide strong evidence to support the use of scrap tire materials in combination with cement and SH-85 for sustainable and resilient infrastructure construction on peat soils. The next chapter will consolidate the conclusions of this study, discuss its broader implications, and offer recommendations for future research and practical implementation.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 General Remarks

The stabilization of highly decomposed sapric peat in Kota Samarahan using a novel blend of cement (C), rubber crumb (RC), and SH85; a silica-based additive represents a significant advancement in sustainable subgrade improvement for tropical organic soils.

This investigation contributes a pioneering assessment of a hybrid stabilization mix, examining the behavioural trends of treated peat in relation to strength, settlement, and slope stability performance under embankment loading. The results reveal that the addition of SH85 and rubber crumb, in combination with low cement content, led to improved mechanical properties and microstructural densification which confirming the suitability of this approach for peat treatment under both laboratory and field-simulated conditions.

Notably, a minimum stabilized layer thickness of 300 mm was found to provide sufficient performance for embankments up to 2 m in height under low-traffic road conditions. Increasing the thickness to 500 mm did not yield proportionally significant improvements in either settlement control or factor of safety. These findings demonstrate that site-specific optimization of stabilizer dosage and thickness can result in both technical and economic efficiency, reducing overdesign and material usage.

Moreover, the experimental data and numerical modelling revealed clear behavioural improvements over untreated peat, which was otherwise characterized by excessive water content, poor bearing capacity, and high compressibility. In this study, the

numerical models assumed idealized conditions and uniform material properties and field trials were not conducted within the project timeline.

6.2 Concluding Remarks

This research addressed the following core objectives. Key findings and conclusions are presented below, mapped directly to each objective:

Objective 1: *To characterize the physical and mechanical properties of natural peat soil and reinforced peat through basic properties determination, unconfined compression strength (UCS) tests, and California bearing ratio (CBR) tests.*

The untreated sapric peat from Kota Samarahan was confirmed to be highly problematic which is unsuitable for direct load bearing without stabilization. The peat was found to be acidic, exhibiting low specific gravity (1.67), high moisture content (580.2%), low ash content (13.17%), and poor mechanical strength (UCS < 50 kPa), which corroborates previous studies on Malaysian peat (Huat et al., 2011; Zainorabidin & Wijeyesekera, 2007a). Upon stabilization using a mixture comprising 5% cement, 15% rubber crumb (RC), and 6% SH85 additive, a peak UCS value of 513.3 kPa was achieved, surpassing untreated values by over 10 times. This represents an order of magnitude improvement in strength, sufficient to meet subgrade criteria for low-volume roads. The addition of rubber crumb improved ductility, while SH85 enhanced strength through secondary pozzolanic reactions. However, further increases in SH85 dosage were found to reduce UCS, indicating the presence of an optimum reactive threshold which is consistent with observations by N. Hassan et al. (2019) and Marto et al. (2016). The highest CBR value of 42 kPa (28-day curing) further validates the mixture's applicability in subgrade pavement systems.

Objective 2: *To evaluate the morphological characteristics of the reinforced peat soil by performing microstructure and morphology analysis using the Scanning Electron Microscope (SEM) images and energy dispersive X-ray spectrometer analysis (EDX).*

SEM analyses revealed significant microstructural densification in treated peat samples. The untreated peat showed a porous, loosely connected fibrous matrix, whereas stabilized samples exhibited crystalline gel formations which is calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) that filling the voids and binding particles. EDX data confirmed the presence of reactive elements (Ca, Si, Al) in higher concentrations post-treatment. The presence of Ca, Si, and Al in treated samples correlated with strength improvements in the treated peat. These chemical and morphological changes are consistent with effective pozzolanic reactions and confirm the physicochemical synergy between cement and SH85 in forming durable cementitious compounds (Ibrahim et al., 2014; Latifi, Horpibulsuk, et al., 2017a; A. Wahab et al., 2021).

Objective 3: *To investigate the settlement performance of the optimum design mixture for the stabilized sub-grade layer using GeoStudio analysis.*

The modified Cam Clay Model more accurately represented peat's compressibility compared to the Mohr-Coulomb Model. The modelling results aligned closely with laboratory performance trends validating the practical applicability of the optimum mix for field-scale embankment.

6.3 Recommendations for Future Work

Considering the findings and limitations encountered in this study, several recommendations are proposed to further advance the understanding and practical implementation of stabilized sapric peat for geotechnical infrastructure. These

recommendations aim to enhance the robustness, generalizability, and long-term sustainability of stabilization strategies for problematic tropical organic soils:

6.3.1 Field-Scale Validation of Laboratory and Numerical Findings

While the current study demonstrates the effectiveness of the stabilization mixture with traditional and nontraditional additives (Pt + 5% Cement + 15% Rubber Crumb + 6% SH85) through laboratory testing and finite element modelling, full-scale field trials are essential to evaluate the performance of the proposed mix under real-world loading, drainage, and climatic conditions. Such validation will enable assessment of settlement behaviour, strength development, and durability under traffic loads and seasonal fluctuations.

6.3.2 Investigation of Long-Term Durability under Environmental Stressors

The long-term behaviour of stabilized peat remains uncertain, particularly under conditions involving cyclic wetting-drying, microbial degradation, temperature variation, and acidic leachate exposure. Future studies should examine the aging mechanisms and chemical durability of the stabilized matrix, especially focusing on the resilience of cementitious gels and polymer bonds over extended periods.

6.3.3 Assessment of Alternative and Locally Sourced Eco-Friendly Binders

To further promote environmental sustainability and cost reduction, future research should explore alternative binders such as geopolymer-based activators, rice husk ash, palm oil fuel ash (POFA), or industrial slags. These materials may offer similar or superior pozzolanic properties while reducing carbon footprint and dependency on ordinary Portland cement (OPC).

6.3.4 Integration of Multi-Objective Optimization and Life-Cycle Cost Assessment

Future studies should employ multi-objective optimization algorithms such as genetic algorithms, artificial neural networks (ANNs), or particle swarm optimization (PSO) to balance mechanical performance, cost, durability, and environmental impact in the design of stabilization mixes. Furthermore, life-cycle cost analysis (LCCA) and carbon footprint evaluations should be incorporated to guide sustainable decision-making for large-scale infrastructure planning.

6.4 Closing Remarks

This research demonstrates that integrating cement, SH-85 and scrap tire materials significantly enhances the geotechnical performance of peat, offering a sustainable and technically viable solution for infrastructure development in problematic soils. The laboratory finding, reinforced by numerical modelling, provide strong foundation for future application and large-scale implementation.

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APPENDICES

Appendix A: Results of Basic Properties

1. Undrained Shear Strength of natural peat

Depth	Undrained shear strength, cu (kPa)			
	1st site	2nd site	3rd site	Average
0.5	12.5	9	16	12.5
1.0	16	16	16	16.0
1.5	17.5	14	18	16.5
2.0	21.5	22.5	25	23.0
2.5	32	36	32.5	33.5
3.0	50	49	54	51.0

2. Moisture content of natural peat

Test no.		1	2	3
Container No.		1A	2A	3A
Mass of cont. + Wet Soil	g	63.451	61.389	64.056
Mass of cont. + Dry Soil	g	17.888	17.273	18.177
Mass of container	g	10.117	9.916	9.905
Moisture Loss	g	45.563	44.116	45.879
Mass of dry sample	g	7.771	7.357	8.272
Moisture Content	%	586.321	599.647	554.630
Average moisture content	%		**580.20**	

3. Specific gravity

(a) Peat

Pycnometer number		1	2	3
Mass of bottle + soil + kerosene (g)	m_3	117.20	116.84	117.54
Mass of bottle + soil (g)	m_2	43.08	42.02	42.76
Mass of bottle full of kerosene (g)	m_4	113.04	111.52	111.93
Mass of bottle (g)	m_1	33.08	32.02	32.76
Mass of soil (g)	$m_2 - m_1$	10.00	10.00	10.00

Pycnometer number		1	2	3	A	B	C
Mass of bottle + soil + kerosene (g)	m_3	72.85	72.69	72.57	73.36	72.79	74.59
Mass of bottle + soil (g)	m_2	37.67	37.56	37.69	38.34	37.50	40.38
Mass of bottle full of kerosene (g)	m_4	70.48	70.51	70.14	70.99	70.60	71.85
Mass of bottle (g)	m_1	31.19	31.51	31.19	31.82	31.48	33.14
Mass of soil (g)	$m_2 - m_1$	6.48	6.05	6.50	6.52	6.02	7.24
Mass of kerosenes in full bottle (g)	$m_4 - m_1$	39.29	39.00	38.95	39.17	39.12	38.70
Mass of kerosene used (g)	$m_3 - m_2$	35.18	35.13	34.88	35.02	35.29	34.21
Volume of soil particle (ml)	$(m_4 - m_1) - m_3 - m_2$	4.11	3.87	4.08	4.15	3.83	4.49
Specific gravity, G_s	$Gs = \frac{(m_2 - m_1) \times G_{kerosene}}{(m_4 - m_1) - (m_3 - m_2)}$	1.26	1.25	1.28	1.26	1.26	1.29
Average specific gravity, G_s			**1.26**			**1.27**	

Mass of kerosene used (g) $m_3 - m_2$ 74.12 74.82 74.78

Volume of soil particle (ml) $(m_4 - m_1) - m_3 - m_2$ 5.84 4.69 4.39

Specific gravity, G_s $Gs = \frac{(m_2 - m_1) \times G_{kerosene}}{(m_4 - m_1) - (m_3 - m_2)}$ 1.40 1.75 1.87

Average specific gravity, G_s **1.67**

(b) Rubber crumb

(c) Rubber powder

Pycnometer number		1	2	3	A	B	C
Mass of bottle + soil + kerosene (g)	m_3	40.50	40.46	40.02	40.65	40.66	39.95
Mass of bottle + soil (g)	m_2	24.58	24.64	25.11	24.61	25.20	24.75
Mass of bottle full of kerosene (g)	m_4	38.92	38.84	38.03	38.71	38.86	37.97
Mass of bottle (g)	m_1	18.56	18.99	19.52	18.56	18.99	19.52
Mass of soil (g)	$m_2 - m_1$	6.02	5.65	5.59	6.05	6.21	5.23
Mass of kerosenes in full bottle (g)	$m_4 - m_1$	20.36	19.86	18.51	20.15	19.88	18.45
Mass of kerosene used (g)	$m_3 - m_2$	15.92	15.82	14.91	16.04	15.47	15.20
Volume of soil particle (ml)	$(m_4 - m_1) - m_3 - m_2$	4.44	4.04	3.61	4.11	4.41	3.25
Specific gravity, G_s	$Gs = \frac{(m_2 - m_1) \times G_{kerosene}}{(m_4 - m_1) - (m_3 - m_2)}$	1.07	1.11	1.22	1.16	1.11	1.27
Average specific gravity, G_s			**1.13**			**1.18**	

4. Organic and ash content

Test no.		1	2	3
Mass of crucible	g	36.364	36.504	34.849
Mass of crucibe + 10g oven dried sample, m_1	g	46.425	46.494	44.910
Mass of oven dried sample, A	g	10.061	9.990	10.061
Mass of crucibe + sample after heated for 3 hours at 440°C, m_2	g	37.054	38.803	35.820
$m_1 - m_2$, B	g	9.371	7.691	9.090
Mass of loss sample, C = A - B	g	0.690	2.299	0.971
Ash Content $= \frac{C \times 100}{A}$	%	6.858	23.013	9.651
Organic Content	%	93.142	76.987	90.349
Average Organic Content	%		86.826	
Average Ash Content	%		13.174	

5. Fiber content

Test no.		1	2	3
Mass of filter paper	g	1.494	1.493	1.468
Mass of filter paper + dried sample	g	3.666	3.632	3.600
Mass of dried sample, M_f	g	2.172	2.139	2.132
Initial dry mass, M_s	g	17.925	17.925	17.925
				11.894
Average Fiber Content	%		11.982	

No	Mix design	Liquid Limit (LL)	Shrinkage Limit (SL)
1	Natural Peat	433.50	29.86
2	Dry Peat	114.40	2.81
3	Pt+3R	99.00	2.89
4	Pt+6R	97.50	1.54
5	Pt+9R	99.50	1.68
6	Pt+12R	48.40	2.91
7	Pt+5RC	28.40	3.95
8	Pt+10RC	78.00	0.94
9	Pt+15RC	85.50	1.06
10	Pt+5RP	79.20	2.03
11	Pt+10RP	88.00	1.61
12	Pt+15RP	84.00	1.03

6. Liquid Limit

and Shrinkage Limit

7. pH value

Design Mixture	pH
Unreinforced Peat	3.00
Pt + 5% C	10.12
Pt + 3% SH-85	11.26
Pt + 6% SH-85	11.48
Pt + 9% SH-85	11.62
Pt + 12% SH-85	11.87
Pt + 5%C + 5% RC	10.48
Pt + 5%C + 10% RC	10.77
Pt + 5%C + 15% RC	10.78
Pt + 5%C + 5% RP	10.24

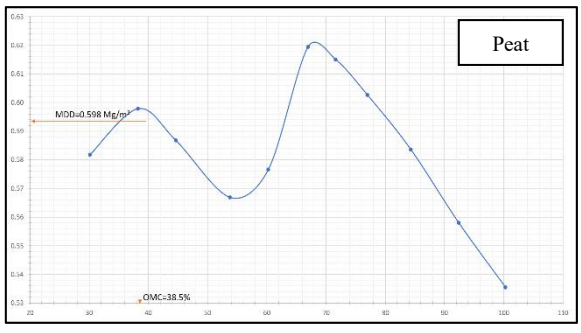
Pt + 5%C + 10% RP	10.51
Pt + 5%C + 15% RP	10.47
Pt + 5%C + 5% RC + 3% SH-85	11.39
Pt + 5%C + 5% RC + 6% SH-85	11.79
Pt + 5%C + 5% RC + 9% SH-85	11.87
Pt + 5%C + 5% RC + 12% SH-85	12.08
Pt + 5%C + 10% RC + 3% SH-85	11.74
Pt + 5%C + 10% RC + 6% SH-85	11.70
Pt + 5%C + 10% RC + 9% SH-85	11.83
Pt + 5%C + 10% RC + 12% SH-85	12.62
Pt + 5%C + 15% RC + 3% SH-85	11.57
Pt + 5%C + 15% RC + 6% SH-85	11.92
Pt + 5%C + 15% RC + 9% SH-85	12.58
Pt + 5%C + 15% RC + 12% SH-85	12.43
Pt + 5%C + 5% RP + 3% SH-85	11.67
Pt + 5%C + 5% RP + 6% SH-85	11.69
Pt + 5%C + 5% RP + 9% SH-85	11.82
Pt + 5%C + 5% RP + 12% SH-85	12.07
Pt + 5%C + 10% RP + 3% SH-85	11.78
Pt + 5%C + 10% RP + 6% SH-85	11.52
Pt + 5%C + 10% RP + 9% SH-85	11.71
Pt + 5%C + 10% RP + 12% SH-85	12.84
Pt + 5%C + 15% RP + 3% SH-85	11.55
Pt + 5%C + 15% RP + 6% SH-85	11.47
Pt + 5%C + 15% RP + 9% SH-85	12.46
Pt + 5%C + 15% RP + 12% SH-85	12.79

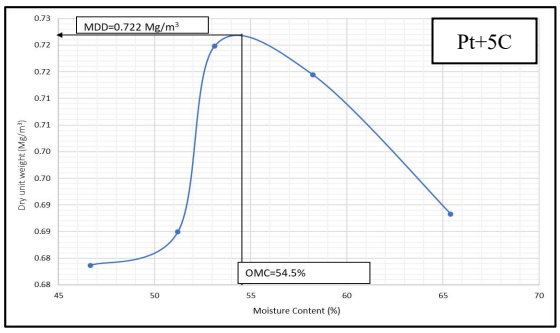
8. Summary of MDD and OMC

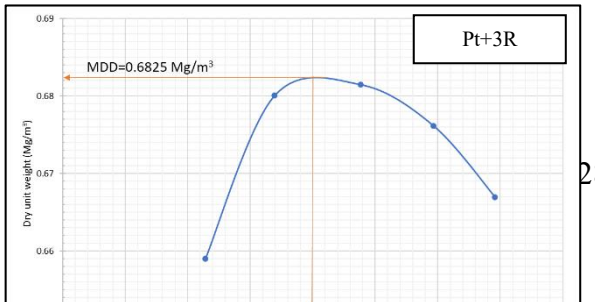
Sample	Design Mix	Maximum Dry Density (kg/m^3)	Optimum Moisture Content (%)
Control sample	Pt only	598	38.5
	Pt + 5% C	722	54.5
	Pt + 3% SH-85	683	50.0
	Pt + 6% SH-85	633	49.0
	Pt + 9% SH-85	670	52.0
	Pt + 12% SH-85	695	49.5
	Pt + 5%C + 5% RC	805	27.0
	Pt + 5%C + 10% RC	772	31.0

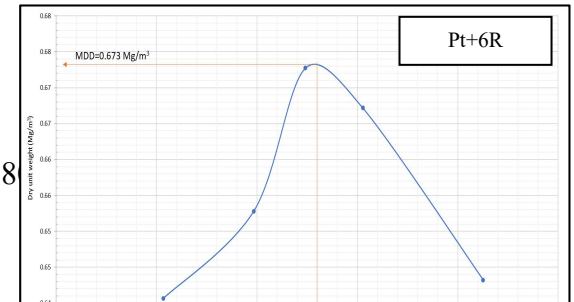
	Pt + 5%C + 15% RC	702	53.0
	Pt + 5%C + 5% RP	695	49.6
	Pt + 5%C + 10% RP	714	47.0
	Pt + 5%C + 15% RP	695	40.5
Reinforced samples	Pt + 5%C + 5% RC + 3% SH-85	761	43.0
	Pt + 5%C + 5% RC + 6% SH-85	751	50.0
	Pt + 5%C + 5% RC + 9% SH-85	702	64.0
	Pt + 5%C + 5% RC + 12% SH-85	705	44.0
	Pt + 5%C + 10% RC + 3% SH-85	785	42.0
	Pt + 5%C + 10% RC + 6% SH-85	798	39.0
	Pt + 5%C + 10% RC + 9% SH-85	694	37.0
	Pt + 5%C + 10% RC + 12% SH-85	749	46.0
	Pt + 5%C + 15% RC + 3% SH-85	751	47.0
	Pt + 5%C + 15% RC + 6% SH-85	753	47.0
	Pt + 5%C + 15% RC + 9% SH-85	705	44.5
	Pt + 5%C + 15% RC + 12% SH-85	715	45.0
	Pt + 5%C + 5% RP + 3% SH-85	736	43.5
	Pt + 5%C + 5% RP + 6% SH-85	704	37.0
	Pt + 5%C + 5% RP + 9% SH-85	696	33.4
	Pt + 5%C + 5% RP + 12% SH-85	767	32.8
	Pt + 5%C + 10% RP + 3% SH-85	739	24.0
	Pt + 5%C + 10% RP + 6% SH-85	666	26.6
	Pt + 5%C + 10% RP + 9% SH-85	697	59.0
	Pt + 5%C + 10% RP + 12% SH-85	661	73.4
	Pt + 5%C + 15% RP + 3% SH-85	628	67.0
	Pt + 5%C + 15% RP + 6% SH-85	613	61.2
	Pt + 5%C + 15% RP + 9% SH-85	636	63.6
	Pt + 5%C + 15% RP + 12% SH-85	682	59.6

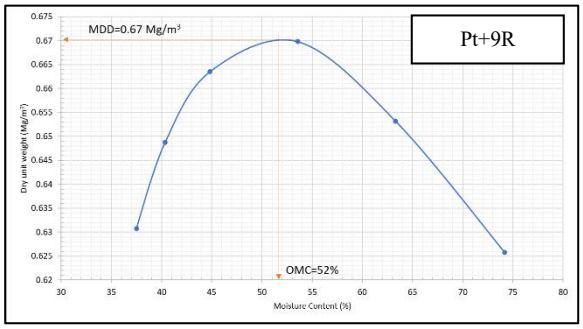
Standard Proctor test results

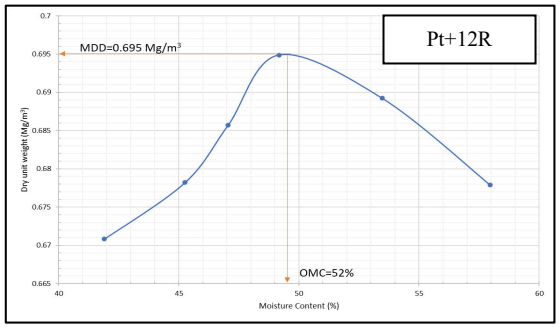


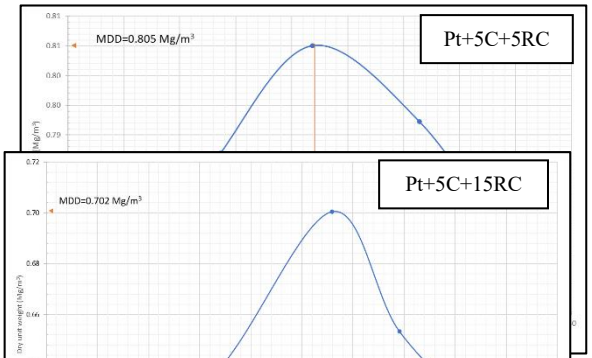


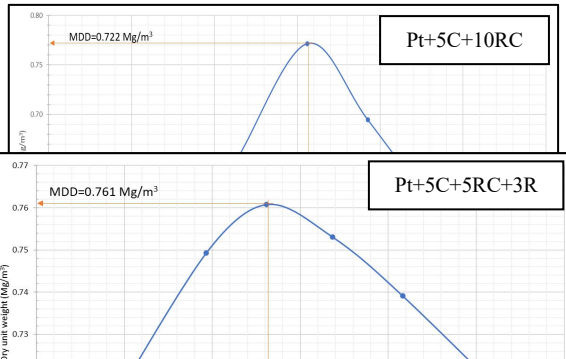





Pt+9R
MDD=0.67 Mg/m³
OMC=52%
Dry unit weight (Mg/m³)
Moisture Content (%)

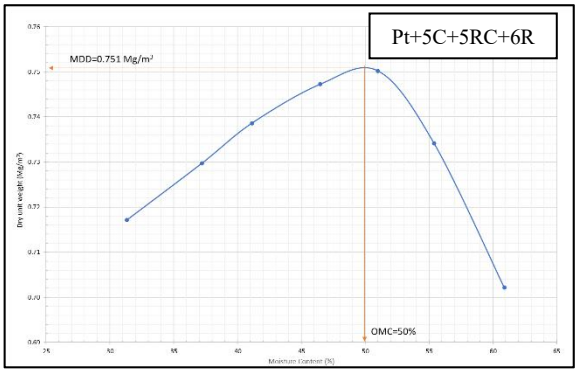

Pt+12R
MDD=0.695 Mg/m³
OMC=52%
Dry unit weight (Mg/m³)
Moisture Content (%)

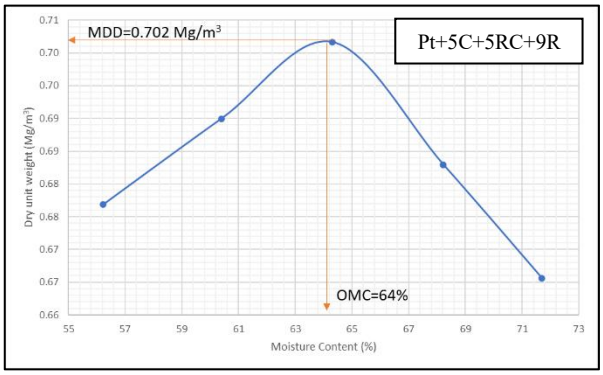

Pt+5C+5RC
MDD=0.805 Mg/m³

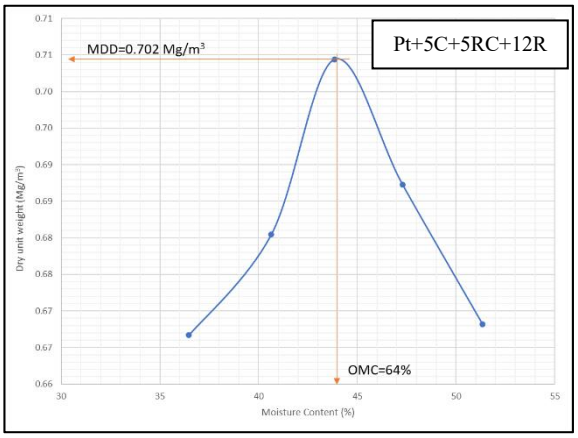

Pt+5C+10RC
MDD=0.722 Mg/m³

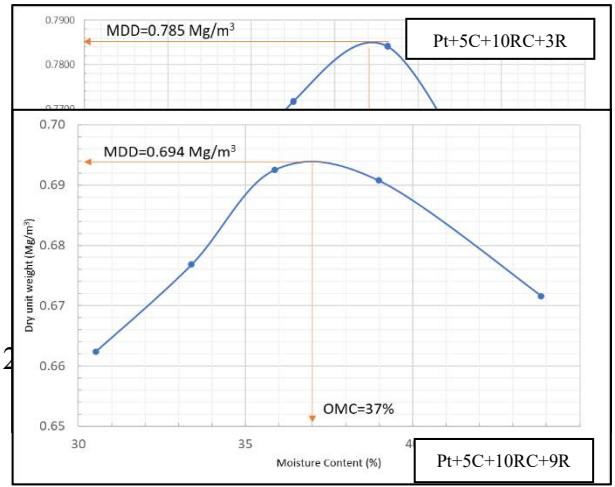
Pt+5C+15RC
MDD=0.702 Mg/m³
OMC=53%
Moisture Content (%)

Pt+5C+5RC+3R
MDD=0.761 Mg/m³
OMC=43%
Dry unit weight (Mg/m³)
Moisture Content (%)

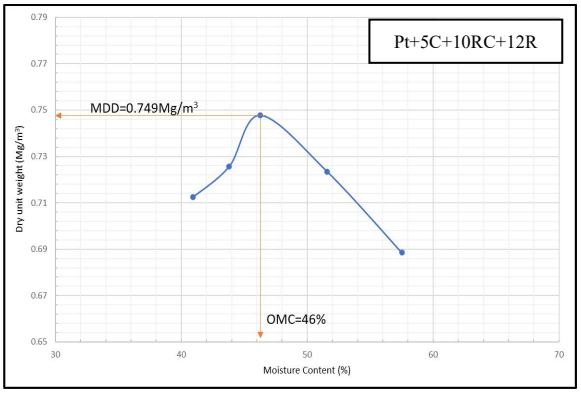

Pt+5C+5RC+6R
MDD=0.751 Mg/m³
OMC=50%
Dry unit weight (Mg/m³)

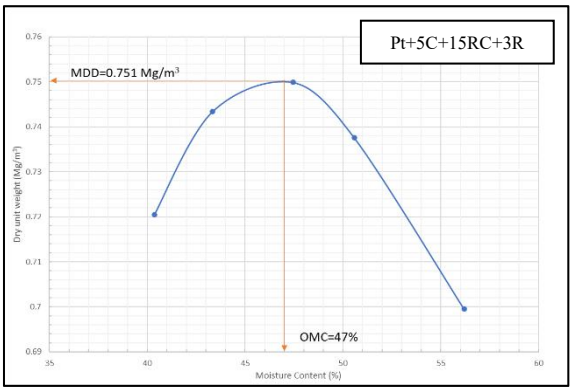

Pt+5C+5RC+9R
MDD=0.702 Mg/m³
OMC=64%
Dry unit weight (Mg/m³)
Moisture Content (%)

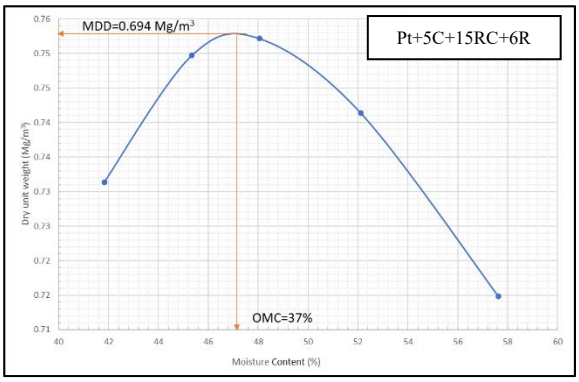

Pt+5C+5RC+12R
MDD=0.702 Mg/m³
OMC=64%
Dry unit weight (Mg/m³)
Moisture Content (%)

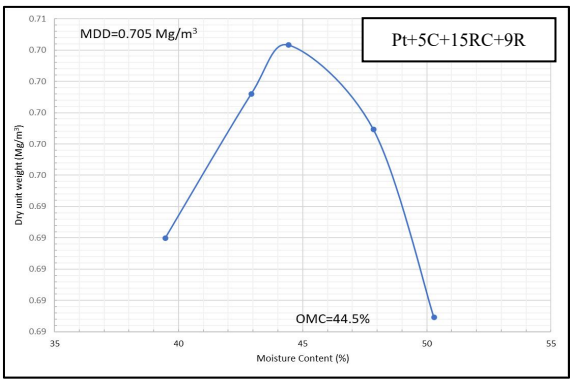

Pt+5C+10RC+3R
MDD=0.785 Mg/m³
MDD=0.694 Mg/m³
OMC=37%
Dry unit weight (Mg/m³)
Moisture Content (%)
Pt+5C+10RC+9R

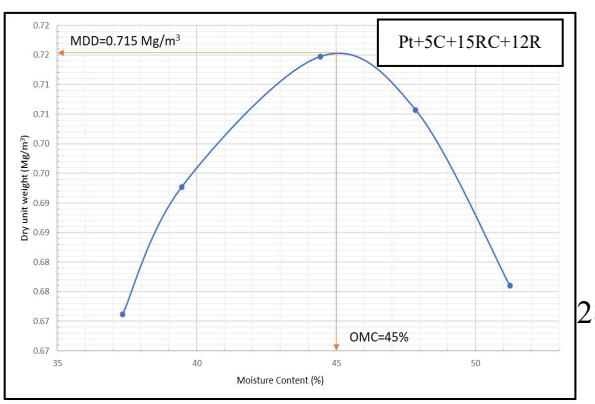

MDD=0.798 Mg/m³

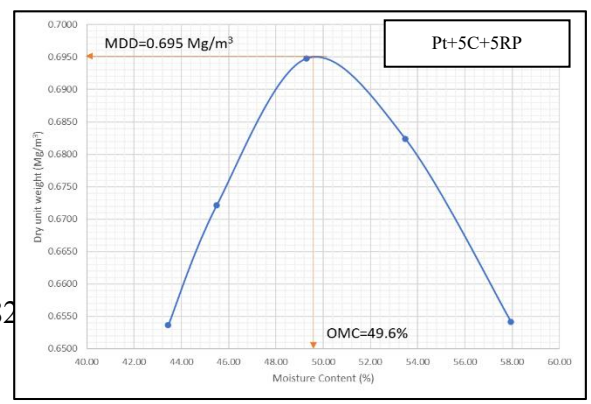

Pt+5C+10RC+12R
MDD=0.749Mg/m³
OMC=46%
Dry unit weight (Mg/m³)
Moisture Content (%)

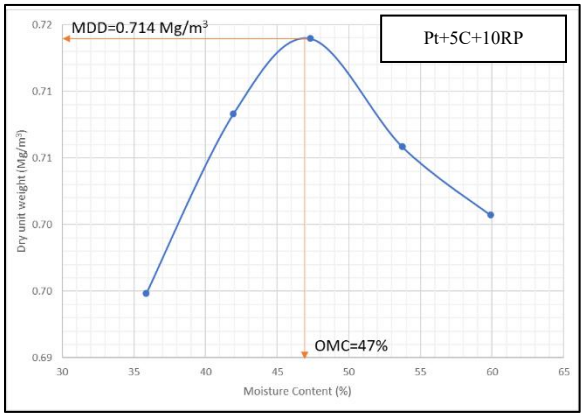

Pt+5C+15RC+3R
MDD=0.751 Mg/m³
OMC=47%
Dry unit weight (Mg/m³)
Moisture Content (%)

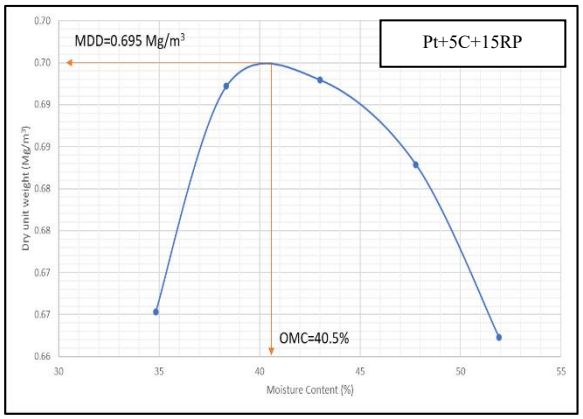

Pt+5C+15RC+6R
MDD=0.694 Mg/m³
OMC=37%
Dry unit weight (Mg/m³)
Moisture Content (%)

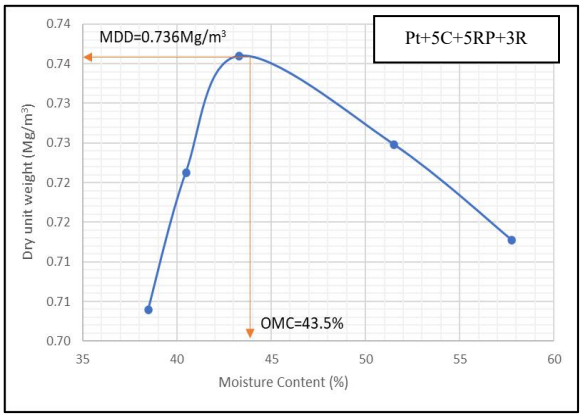

Pt+5C+15RC+9R
MDD=0.705 Mg/m³
OMC=44.5%
Dry unit weight (Mg/m³)
Moisture Content (%)

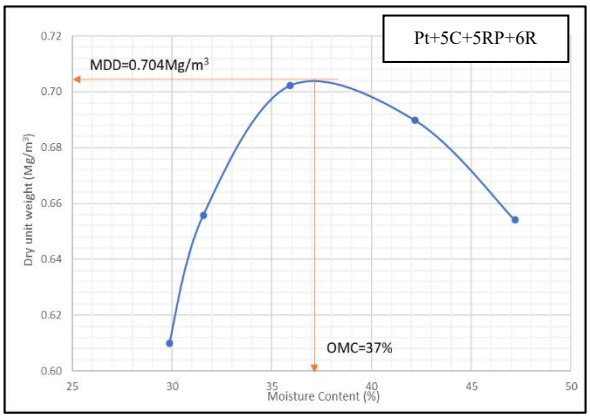

Pt+5C+15RC+12R
MDD=0.715 Mg/m³
OMC=45%
Dry unit weight (Mg/m³)
Moisture Content (%)

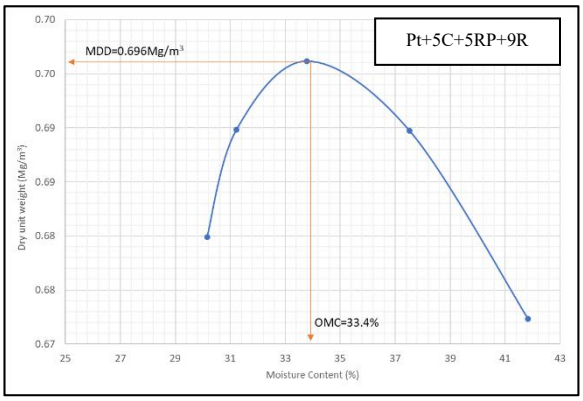

Pt+5C+5RP
MDD=0.695 Mg/m³
OMC=49.6%
Dry unit weight (Mg/m³)
Moisture Content (%)

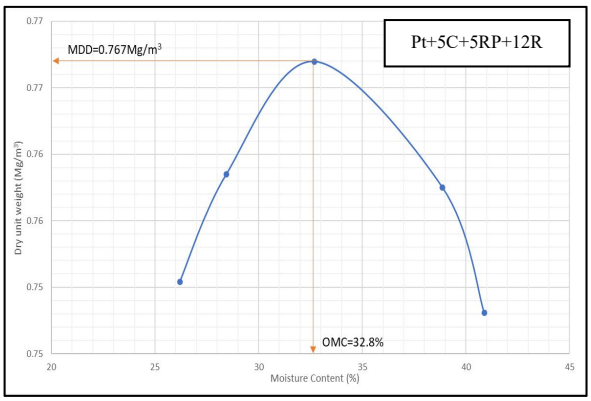

MDD=0.714 Mg/m3
Pt+5C+10RP
OMC=47%
Dry unit weight (Mg/m3)
Moisture Content (%)

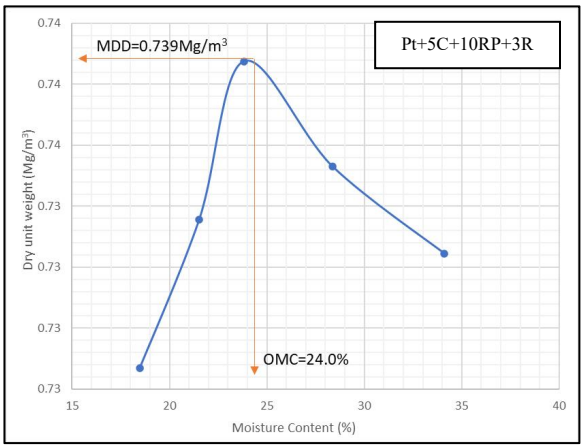

MDD=0.695 Mg/m3
Pt+5C+15RP
OMC=40.5%
Dry unit weight (Mg/m3)
Moisture Content (%)

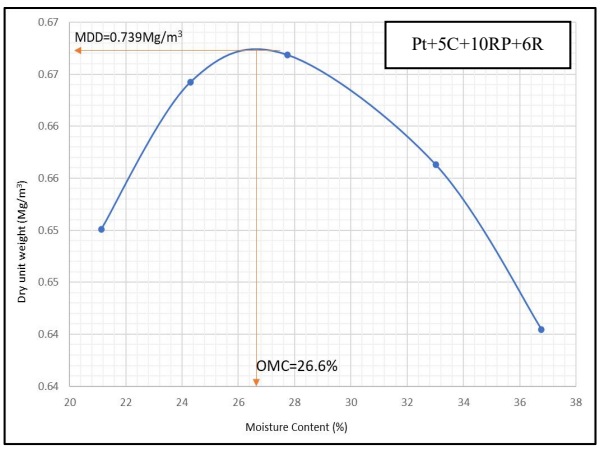

Pt+5C+5RP+3R
MDD=0.736Mg/m³
OMC=43.5%
Dry unit weight (Mg/m³)
Moisture Content (%)

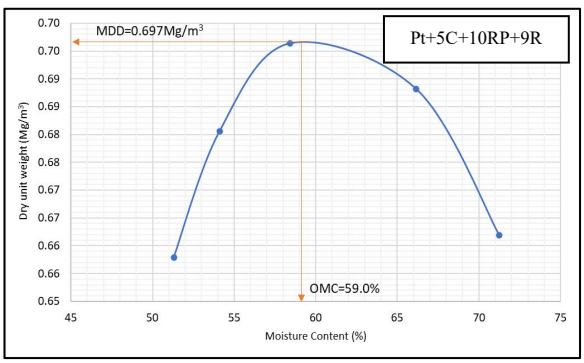

Pt+5C+5RP+6R
MDD=0.704Mg/m³
OMC=37%
Dry unit weight (Mg/m³)
Moisture Content (%)

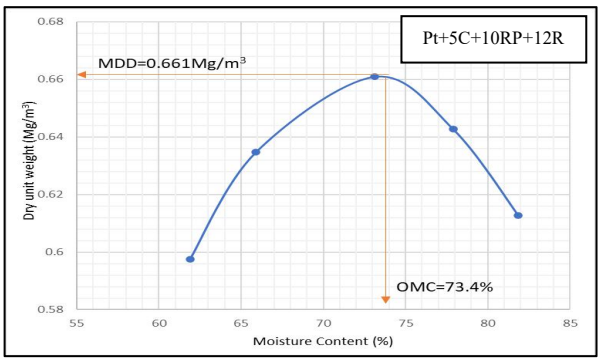

Pt+5C+5RP+9R
MDD=0.696Mg/m³
OMC=33.4%
Dry unit weight (Mg/m³)
Moisture Content (%)

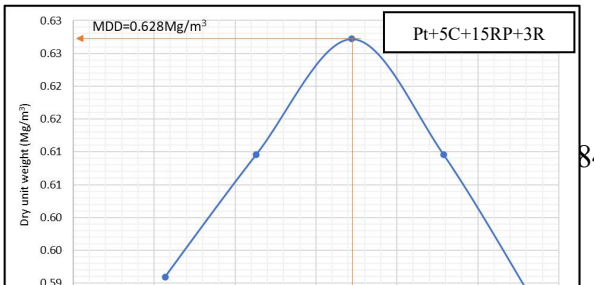

Pt+5C+5RP+12R
MDD=0.767Mg/m³
OMC=32.8%
Dry unit weight (Mg/m³)
Moisture Content (%)

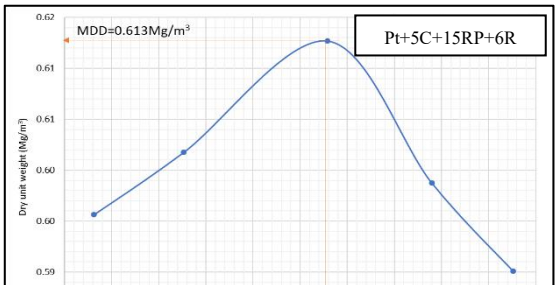

Pt+5C+10RP+3R
MDD=0.739Mg/m³
OMC=24.0%
Dry unit weight (Mg/m³)
Moisture Content (%)

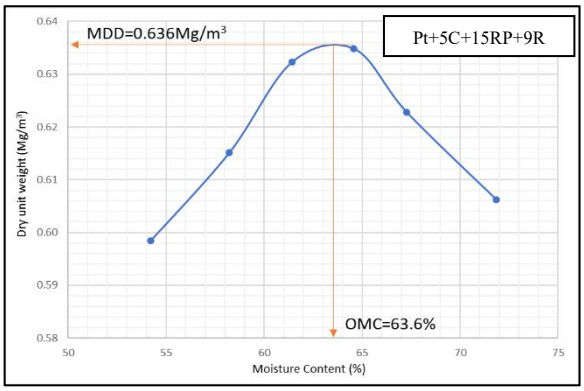

Pt+5C+10RP+6R
MDD=0.739Mg/m³
OMC=26.6%
Dry unit weight (Mg/m³)
Moisture Content (%)

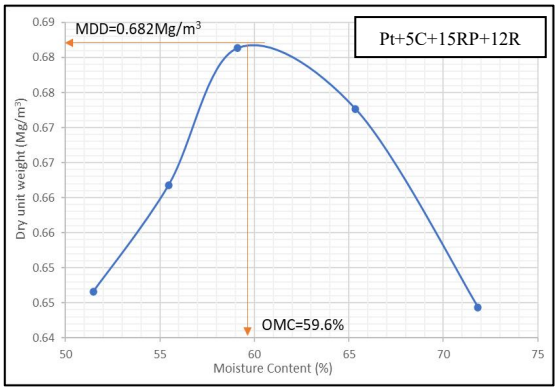

Pt+5C+10RP+9R
MDD=0.697Mg/m³
OMC=59.0%
Dry unit weight (Mg/m³)
Moisture Content (%)


Pt+5C+10RP+12R
MDD=0.661Mg/m³
OMC=73.4%
Dry unit weight (Mg/m³)
Moisture Content (%)


Pt+5C+15RP+3R
MDD=0.628Mg/m³
Dry unit weight (Mg/m³)


Pt+5C+15RP+6R
MDD=0.613Mg/m³
Dry unit weight (Mg/m³)

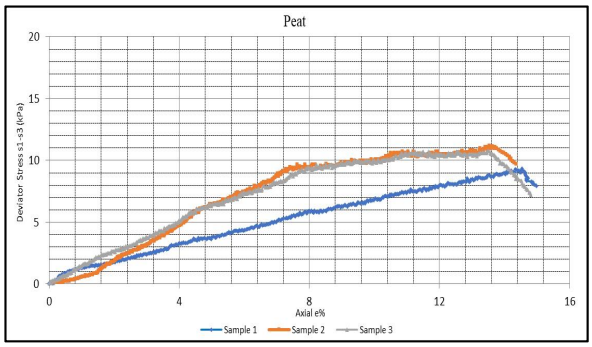


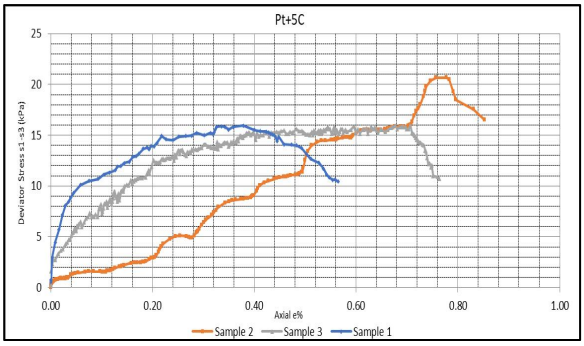


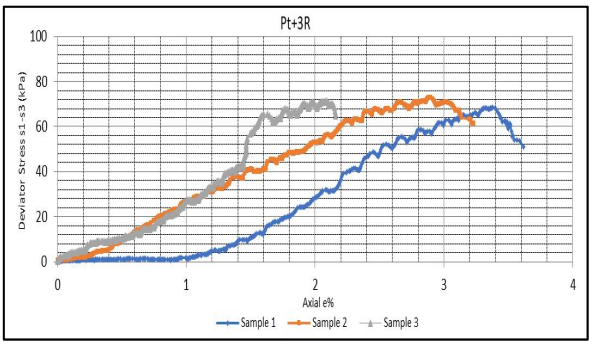
9. Summary of UCS values

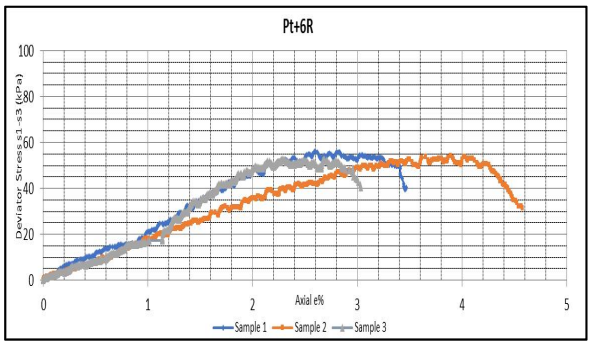
Sample	Design Mix	Unconfined Compressive Strength (kN/m2)		
		Days of Curing		
		7	28	56
Control sample	Pt only	11.2	-	-
	Pt + 5% C	20.7	74.4	205.4
	Pt + 3% SH-85	72.8	84.5	466.4
	Pt + 6% SH-85	56.0	60.4	134.0
	Pt + 9% SH-85	43.0	59.4	85.2
	Pt + 12% SH-85	75.4	89.8	152.6
	Pt + 5%C + 5% RC	193.1	334.9	433.0
	Pt + 5%C + 10% RC	209.3	342.4	400.7
	Pt + 5%C + 15% RC	173.7	187.2	217.5
	Pt + 5%C + 5% RP	79.0	72.8	161.9
	Pt + 5%C + 10% RP	37.4	40.7	52.2
	Pt + 5%C + 15% RP	41.2	50.9	72.0
Reinforced samples	Pt + 5%C + 5% RC + 3% SH-85	156.5	196.7	324.1
	Pt + 5%C + 5% RC + 6% SH-85	129.2	135.5	203.9
	Pt + 5%C + 5% RC + 9% SH-85	86.5	74.4	98.7
	Pt + 5%C + 5% RC + 12% SH-85	72.0	89.5	79.1
	Pt + 5%C + 10% RC + 3% SH-85	398.9	330.6	347.8
	Pt + 5%C + 10% RC + 6% SH-85	117.4	218.1	264.4
	Pt + 5%C + 10% RC + 9% SH-85	74.4	86.1	87.1
	Pt + 5%C + 10% RC + 12% SH-85	110.6	111.4	99.4
	Pt + 5%C + 15% RC + 3% SH-85	252.3	283.4	417.5
	Pt + 5%C + 15% RC + 6% SH-85	293.6	376.1	513.3
	Pt + 5%C + 15% RC + 9% SH-85	47.9	39.5	58.4
	Pt + 5%C + 15% RC + 12% SH-85	66.3	126.3	96.3
	Pt + 5%C + 5% RP + 3% SH-85	58.2	142.8	122.5
	Pt + 5%C + 5% RP + 6% SH-85	40.6	45.8	104.3
	Pt + 5%C + 5% RP + 9% SH-85	38.6	39.5	96.8
	Pt + 5%C + 5% RP + 12% SH-85	31.4	53.4	132.6
	Pt + 5%C + 10% RP + 3% SH-85	18.1	15.7	70.5
	Pt + 5%C + 10% RP + 6% SH-85	16.1	12.4	47.4
	Pt + 5%C + 10% RP + 9% SH-85	73.6	55.7	127.4
	Pt + 5%C + 10% RP + 12% SH-85	87.8	115.3	105.1
	Pt + 5%C + 15% RP + 3% SH-85	43.5	43.5	31.7
	Pt + 5%C + 15% RP + 6% SH-85	58.5	98.6	90.7
	Pt + 5%C + 15% RP + 9% SH-85	28.8	45.8	64.8
	Pt + 5%C + 15% RP + 12% SH-85	43.3	89.3	65.3

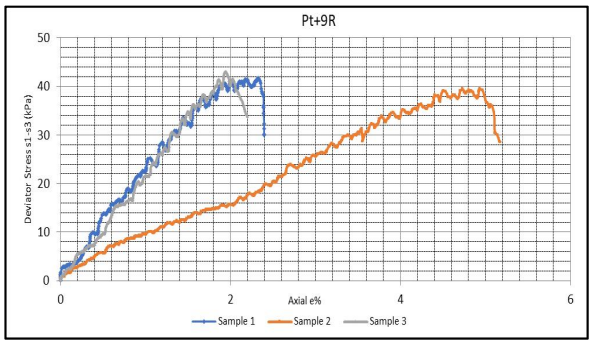
Unconfined compression strength test results (7 days)

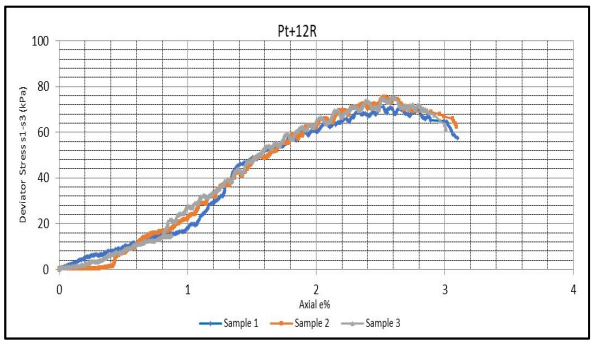


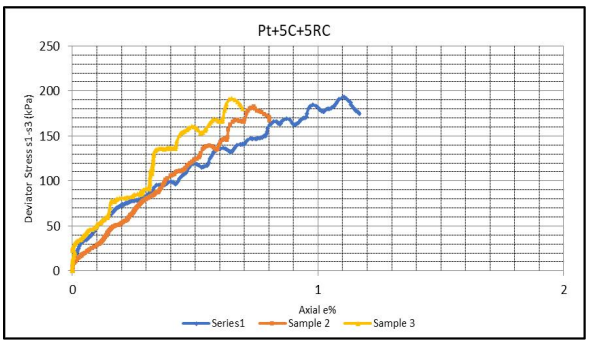


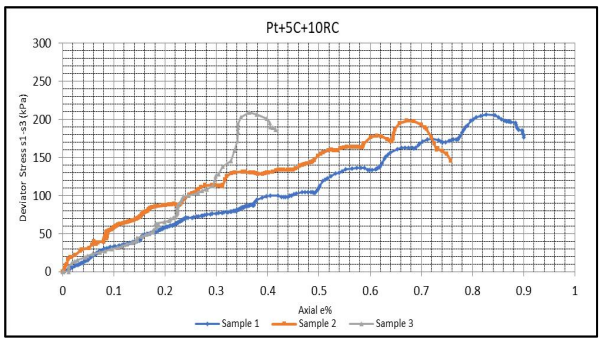


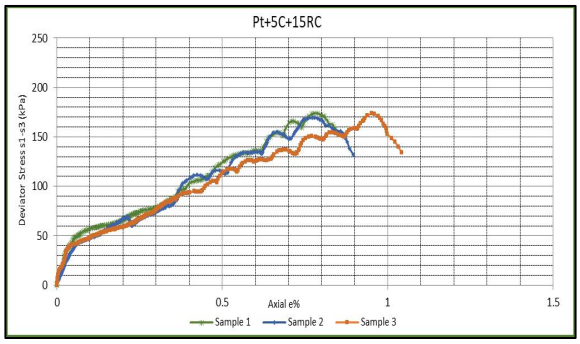


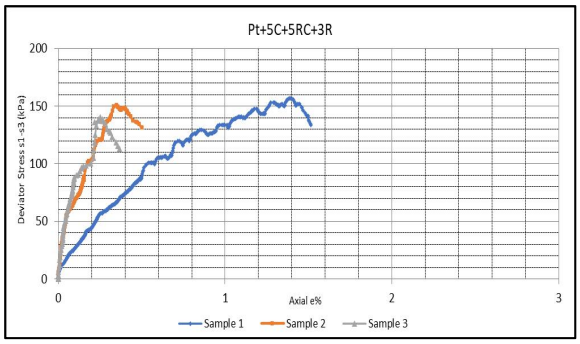


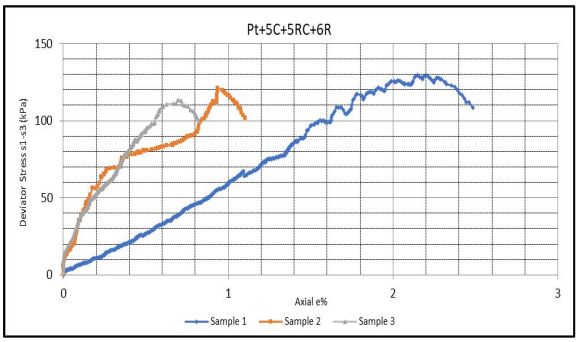


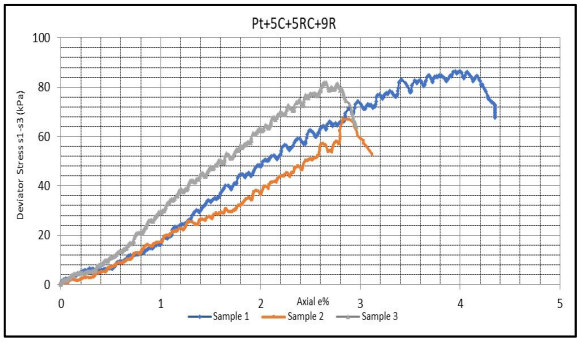


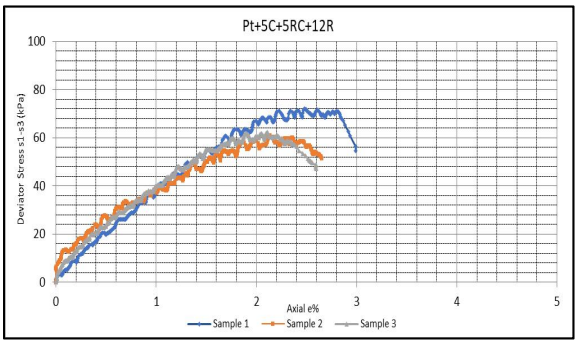


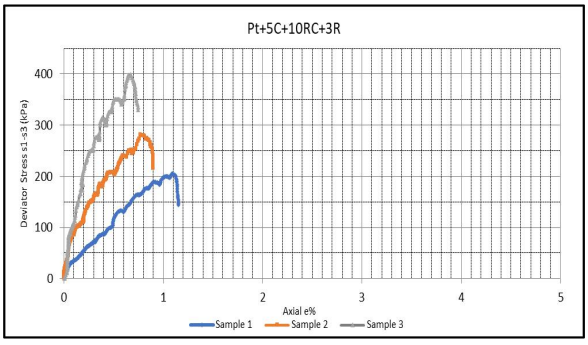

Pt+5C+15RC
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

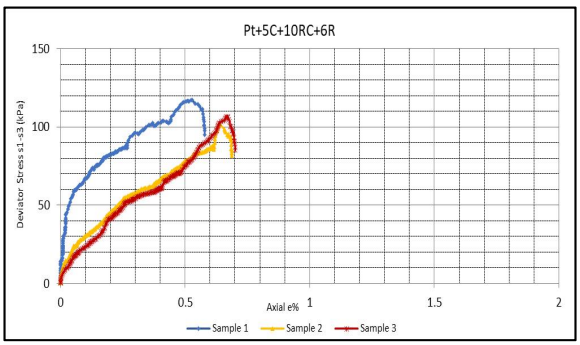

Pt+5C+5RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

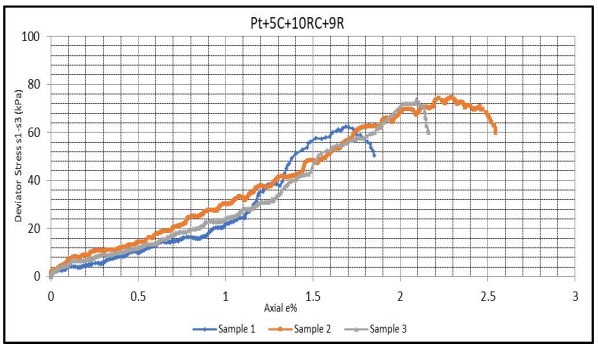

Pt+5C+5RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

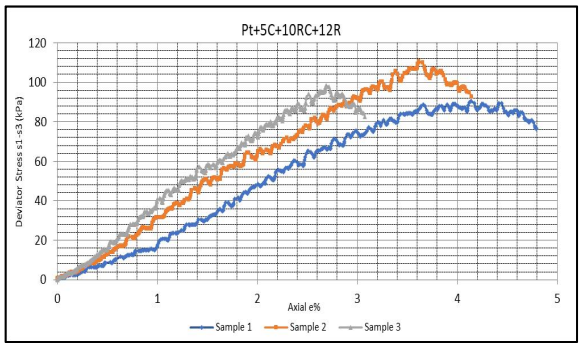

Pt+5C+5RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

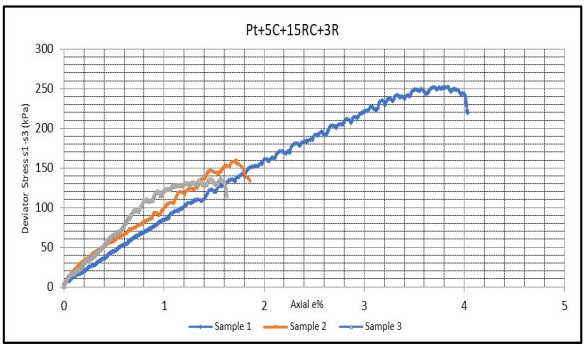

Pt+5C+5RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

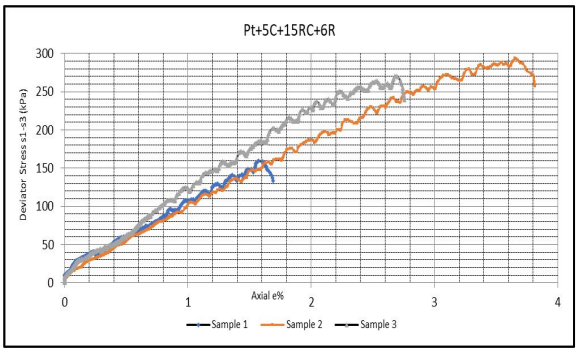

Pt+5C+10RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

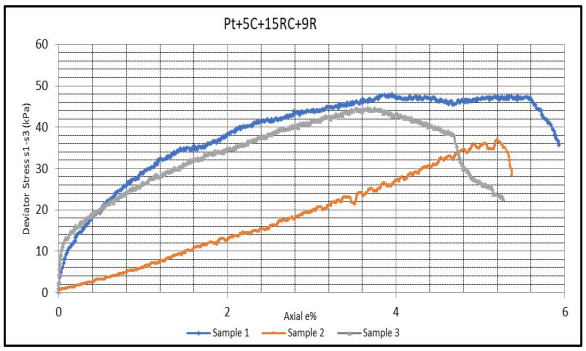

Pt+5C+10RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

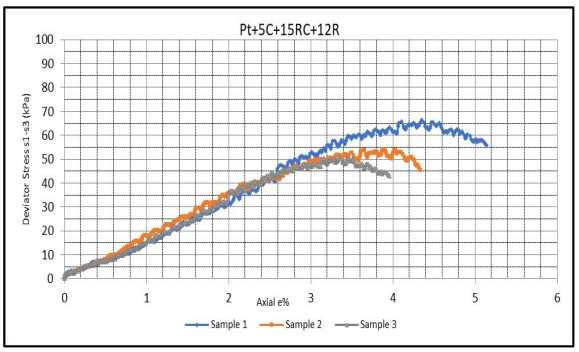

Pt+5C+10RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

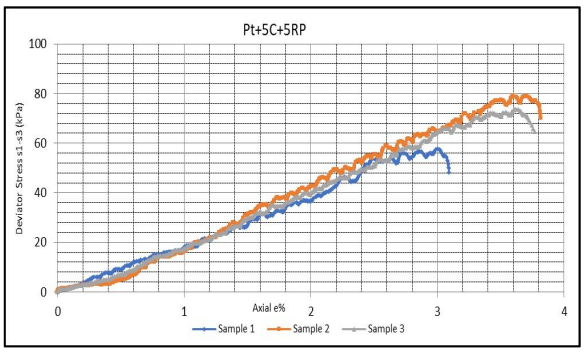

Pt+5C+10RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

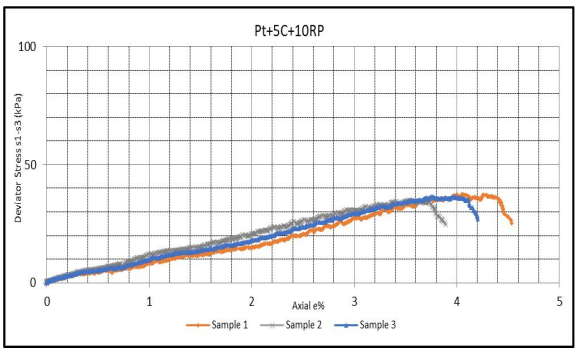

Pt+5C+15RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

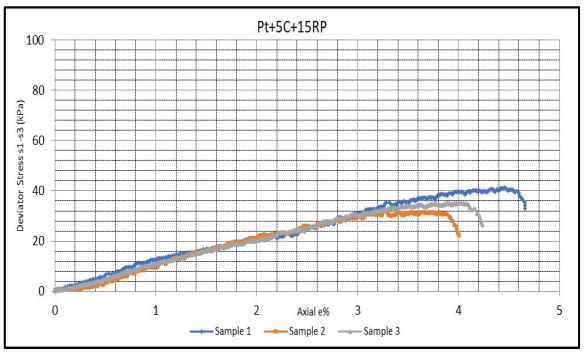

Pt+5C+15RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

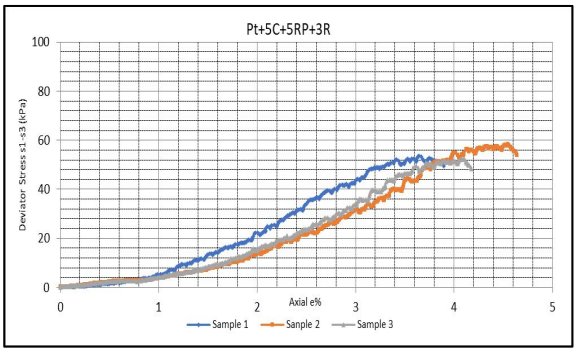

Pt+5C+15RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

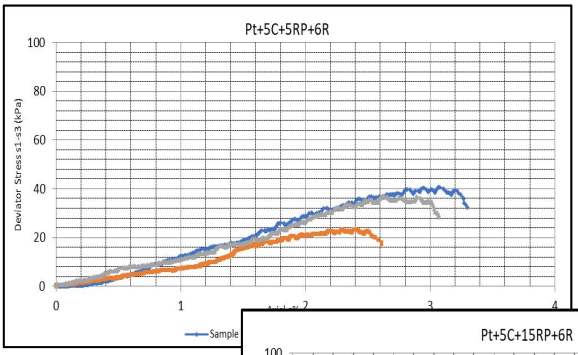

Pt+5C+15RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

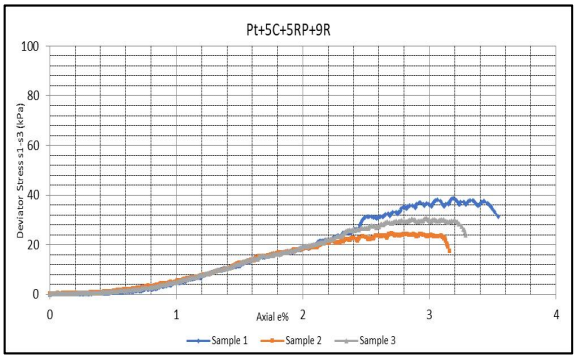

Pt+5C+5RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

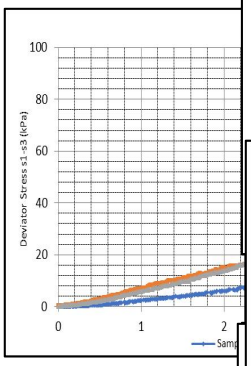

Pt+5C+10RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

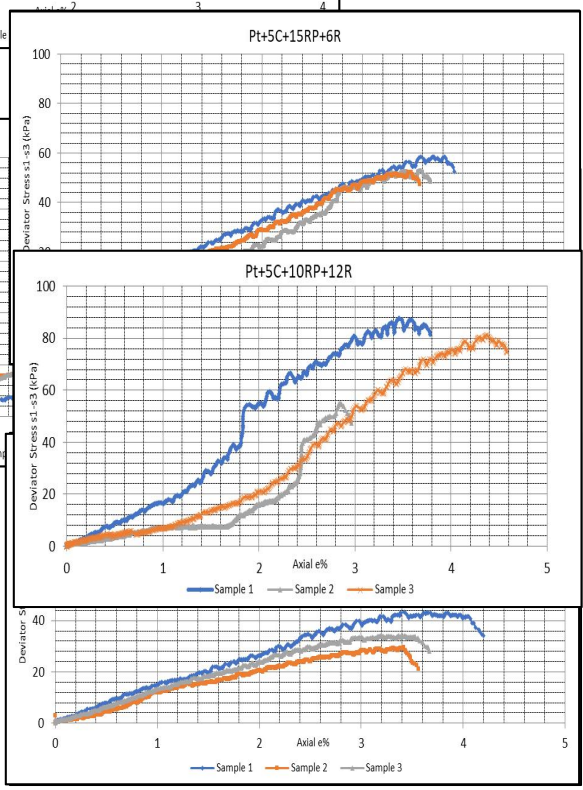

Pt+5C+15RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3



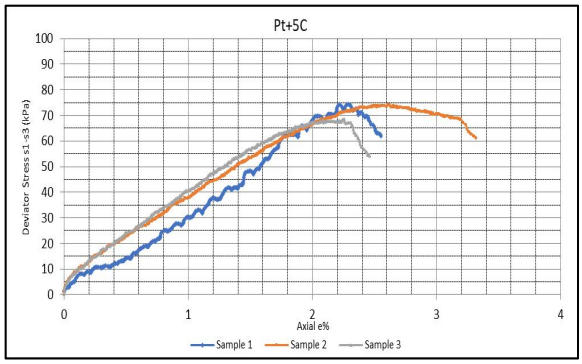


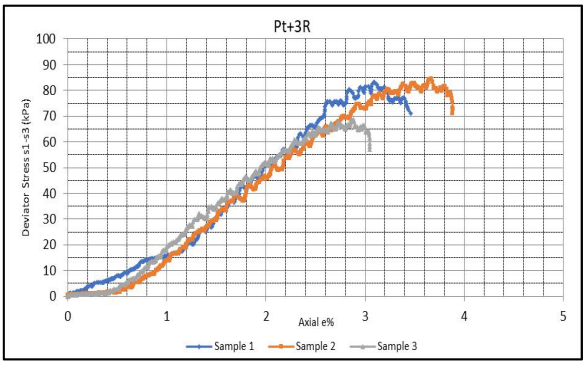


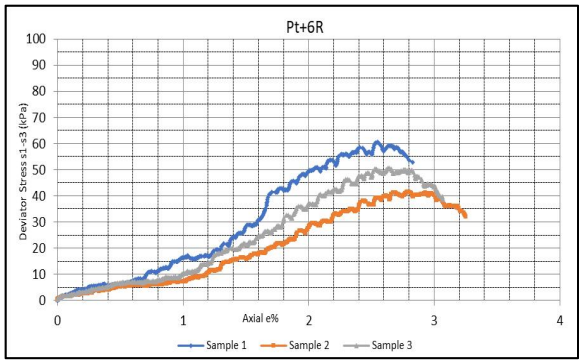


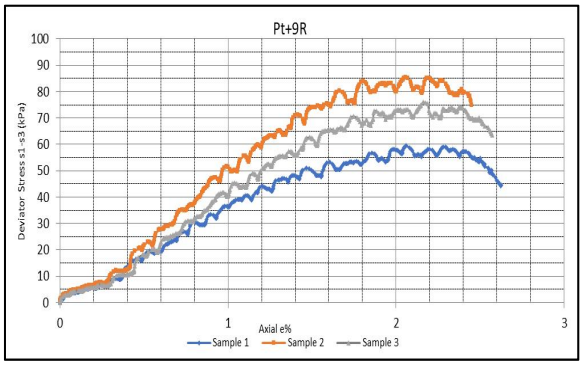


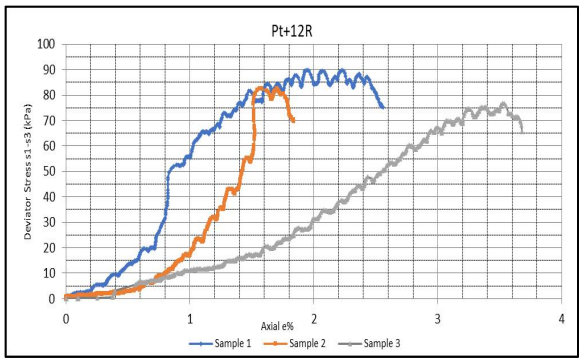
Unconfined compression strength test results (28 days)

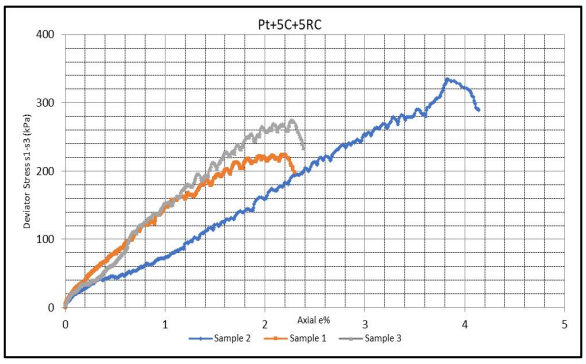

Pt+5C
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

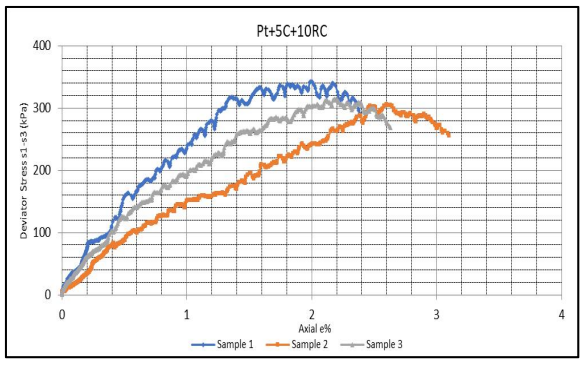

Pt+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

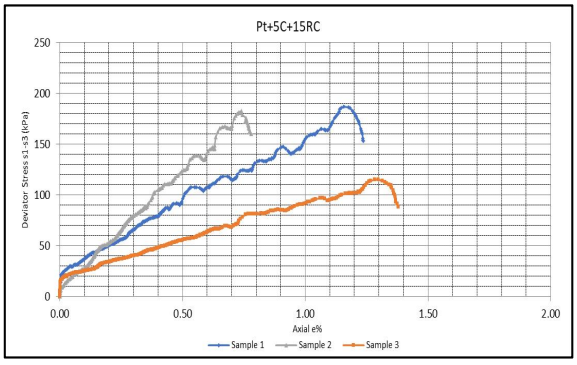

Pt+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

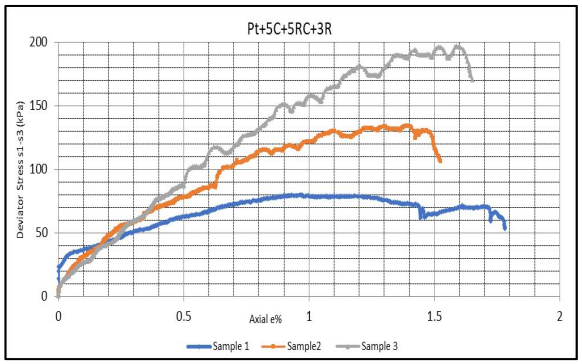

Pt+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

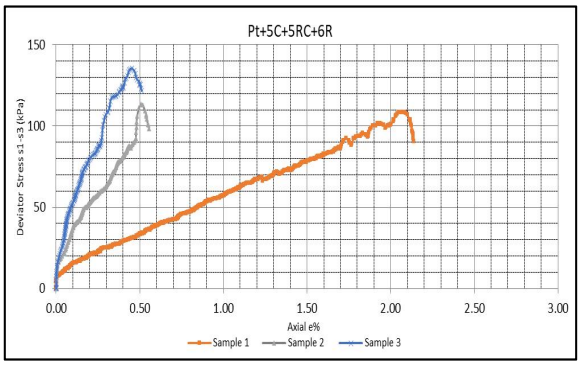

Pt+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

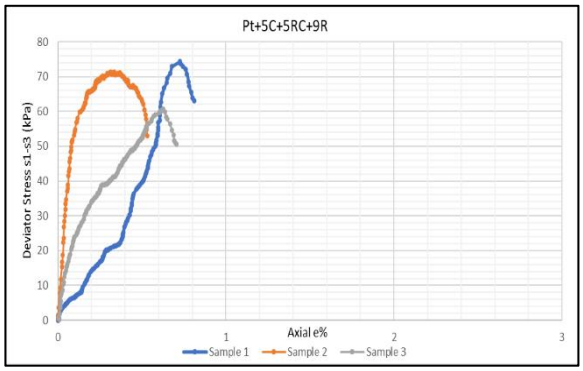

Pt+5C+5RC
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 2
Sample 1
Sample 3

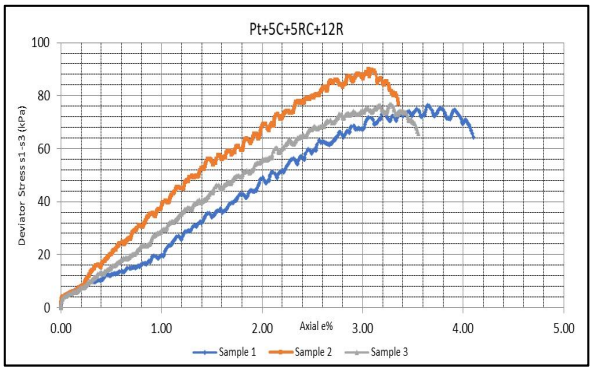

Pt+5C+10RC
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

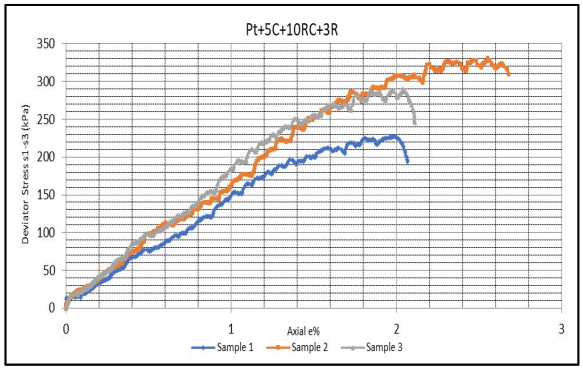

Pt+5C+15RC
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

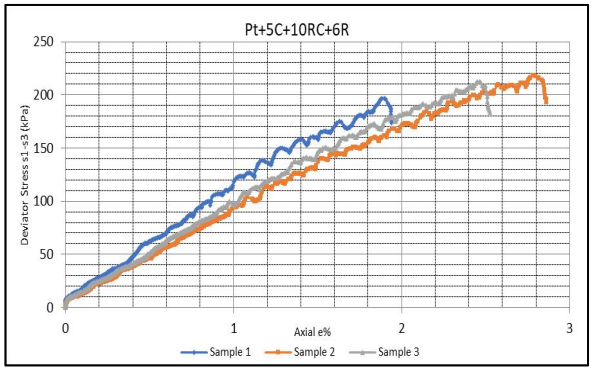

Pt+5C+5RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample2
Sample 3

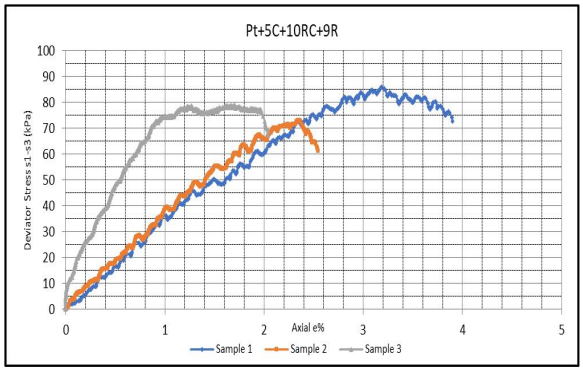

Pt+5C+5RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

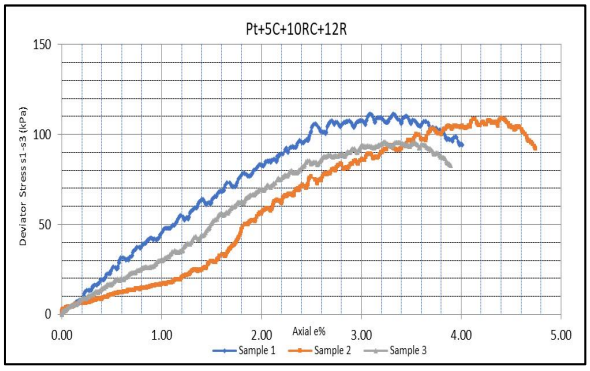

Pt+5C+5RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

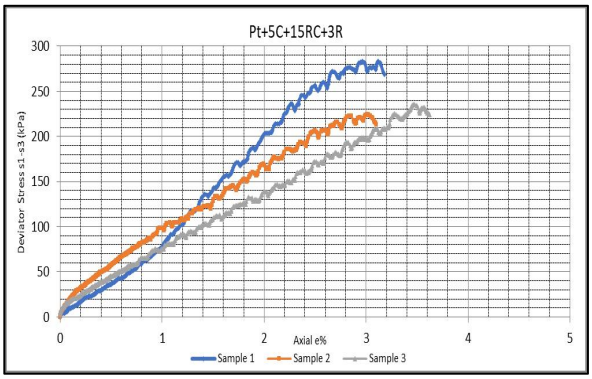

Pt+5C+5RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

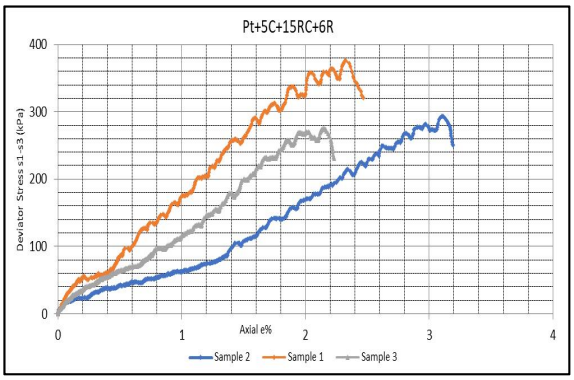

Pt+5C+10RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

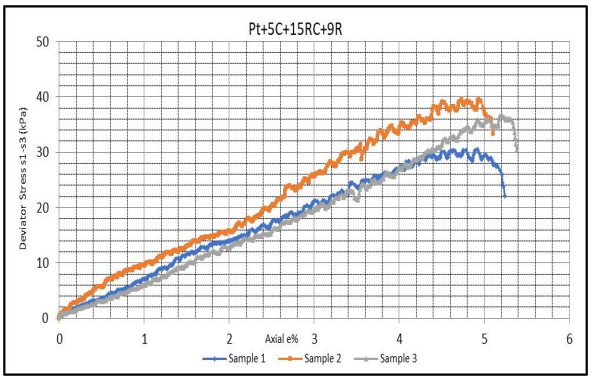

Pt+5C+10RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

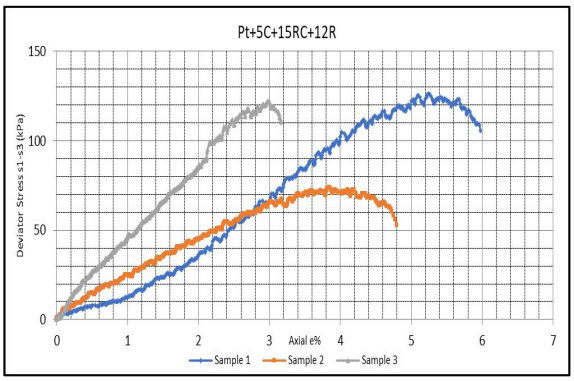

Pt+5C+10RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

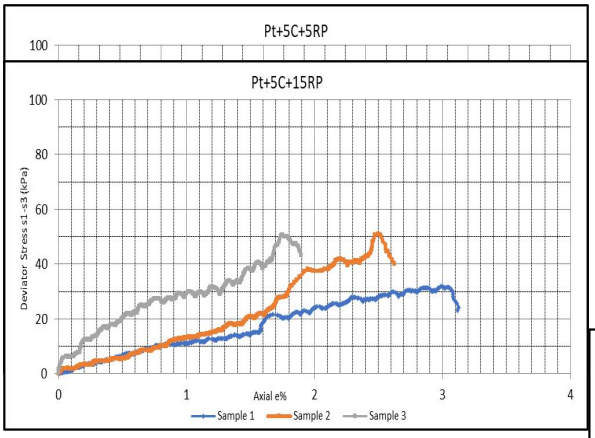

Pt+5C+10RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

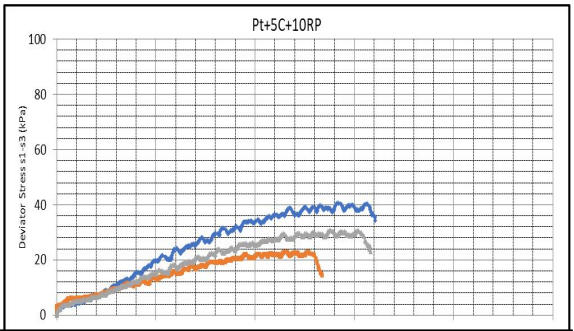

Pt+5C+15RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

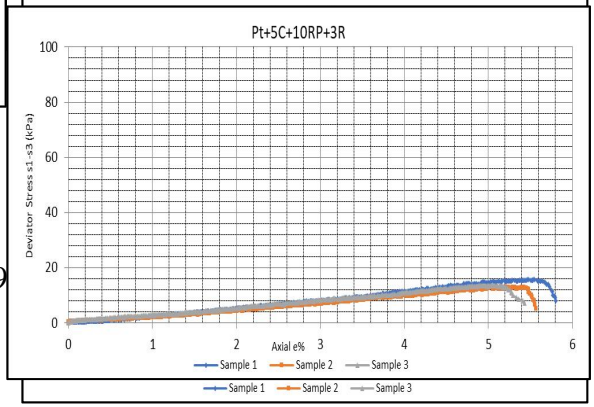

Pt+5C+15RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 2
Sample 1
Sample 3

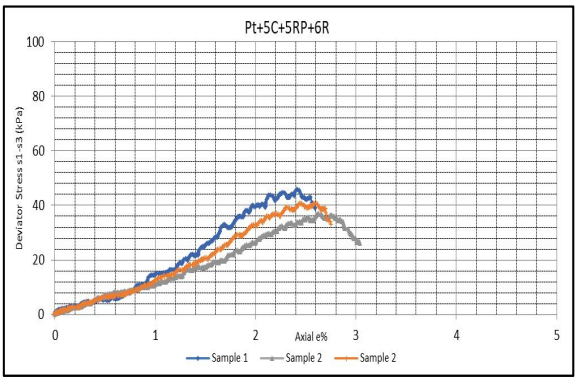

Pt+5C+15RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

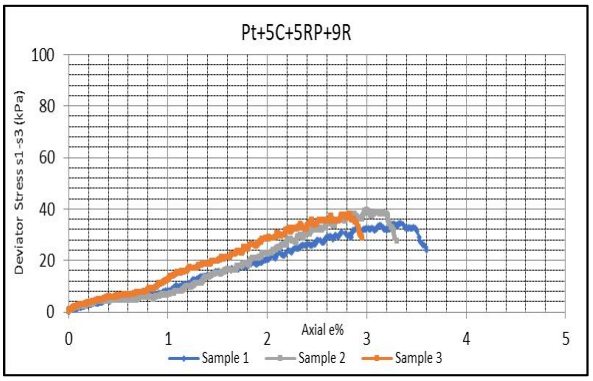

Pt+5C+15RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

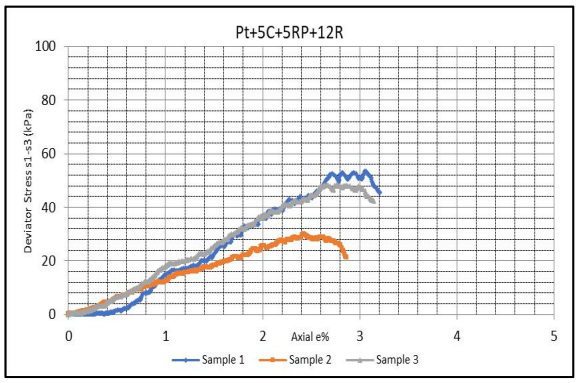

Pt+5C+5RP
Pt+5C+15RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

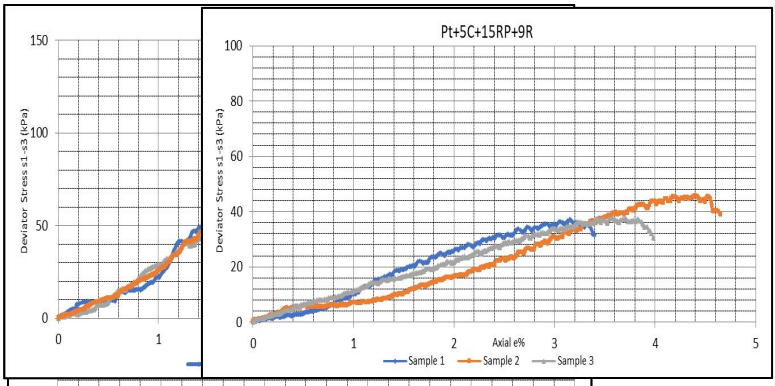

Pt+5C+10RP
Deviator Stress s1-s3 (kPa)

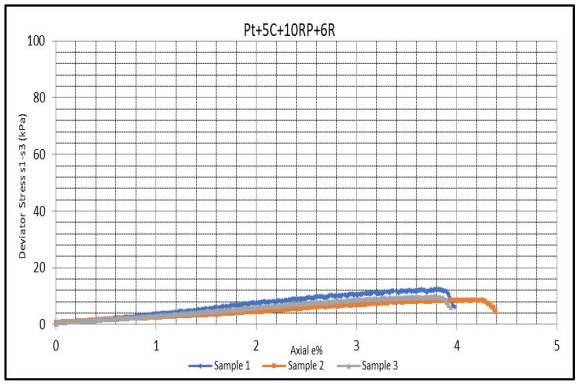

Pt+5C+10RP+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3
Sample 1
Sample 2
Sample 3

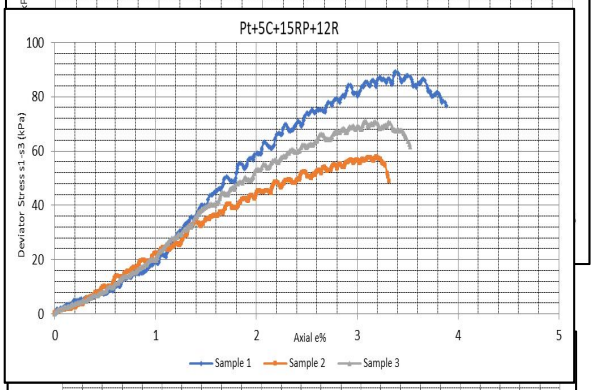

Pt+5C+5RP+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 2

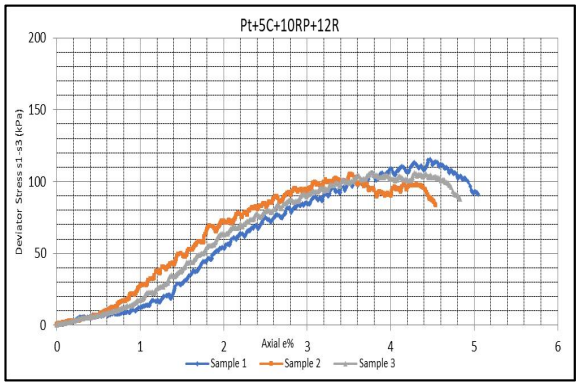

Pt+5C+5RP+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

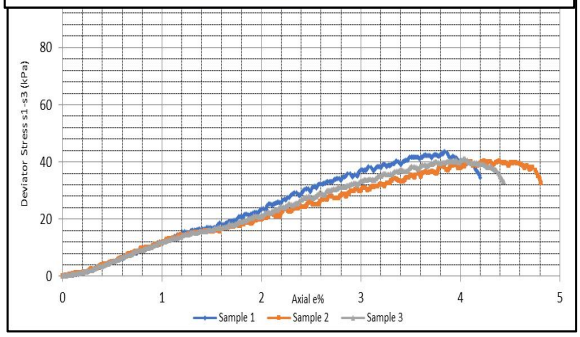

Pt+5C+5RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3


Pt+5C+15RP+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

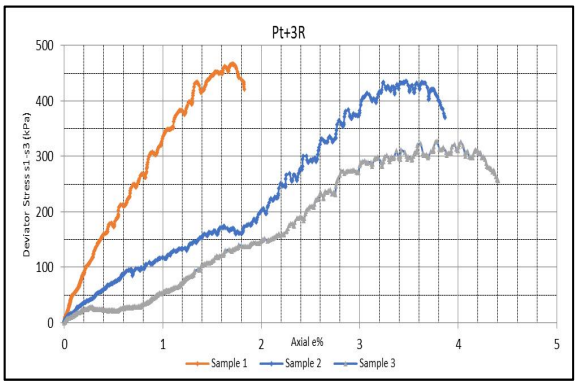

Pt+5C+10RP+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

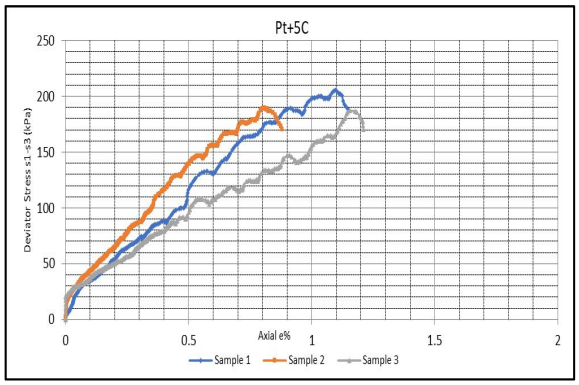

Pt+5C+15RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

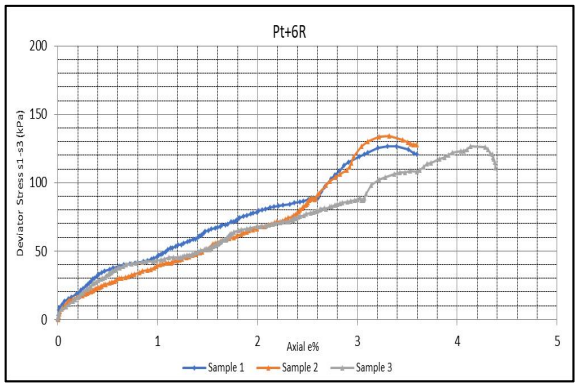

Pt+5C+10RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

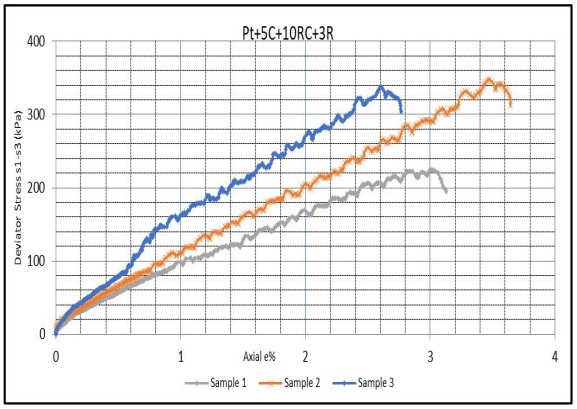

Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

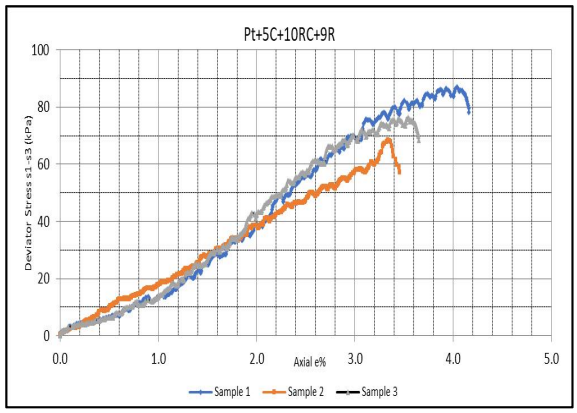
Unconfined compression strength test results (56 days)

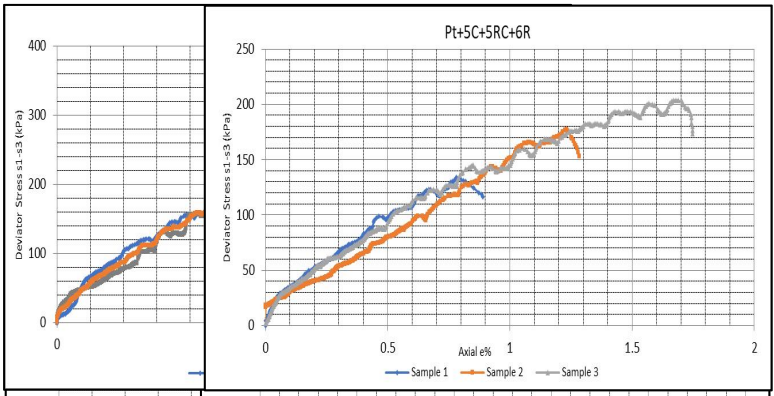


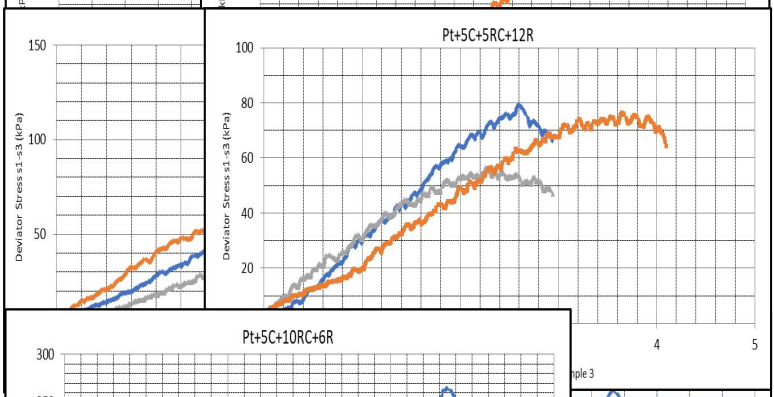

Pt+5C
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

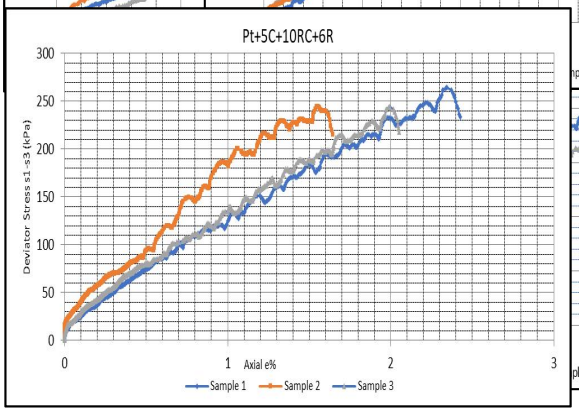

Pt+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

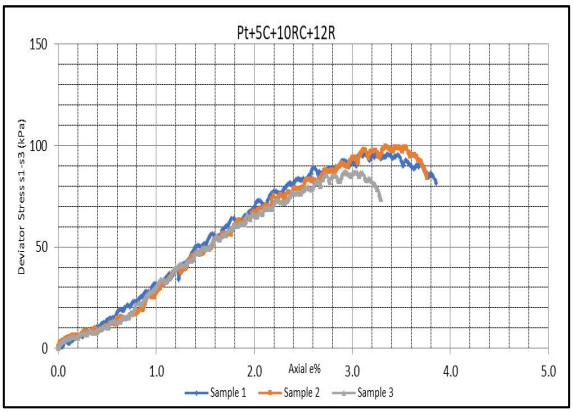

Pt+5C+10RC+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

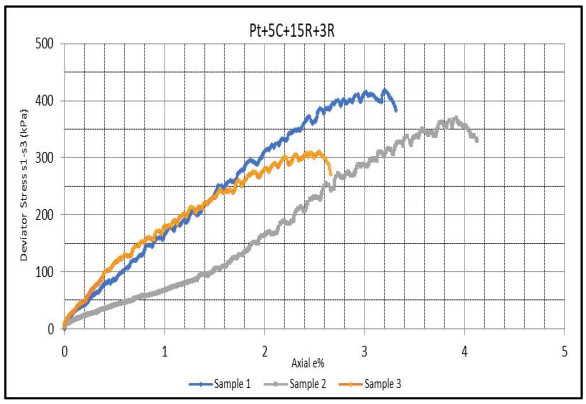

Pt+5C+10RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

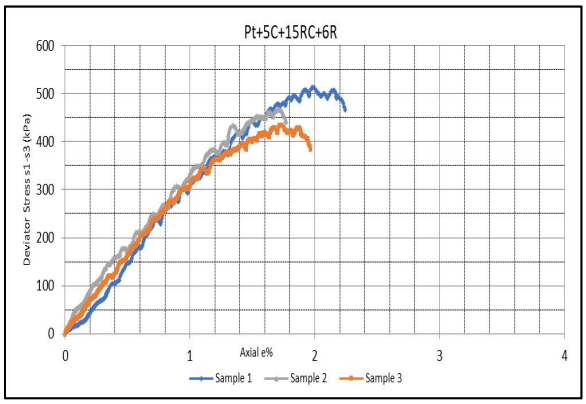

Pt+5C+5RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

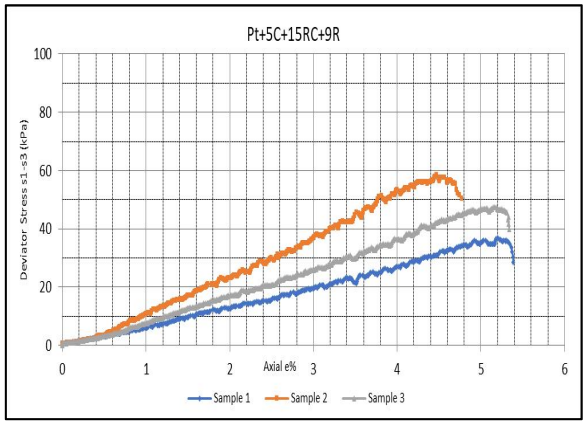

Pt+5C+5RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

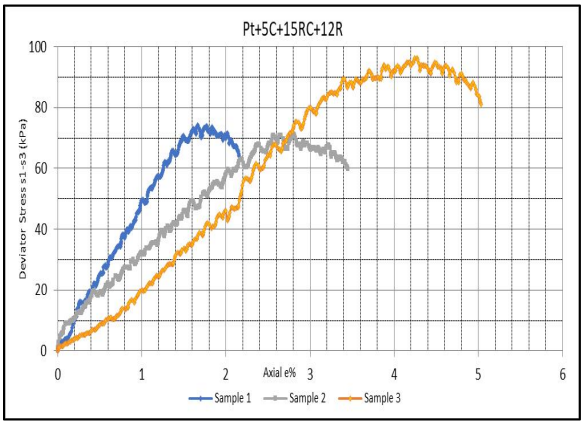

Pt+5C+10RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

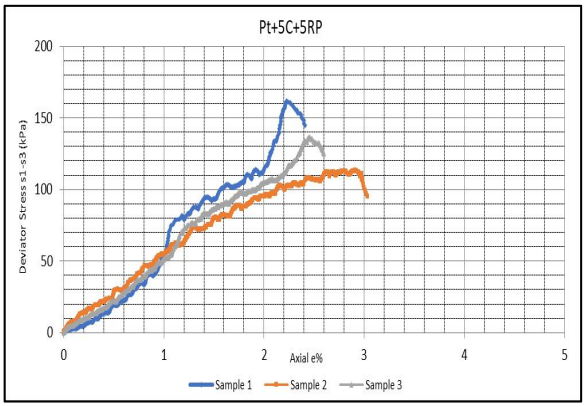

Pt+5C+10RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

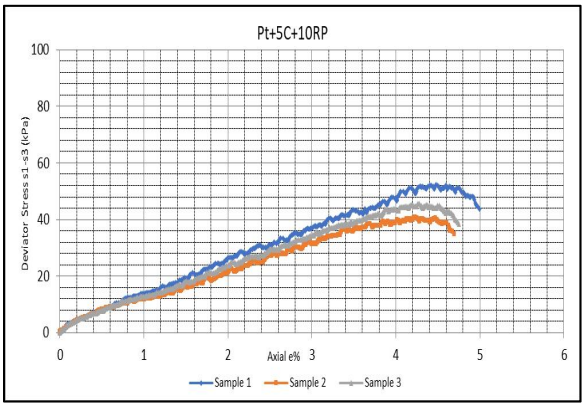

Pt+5C+15R+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

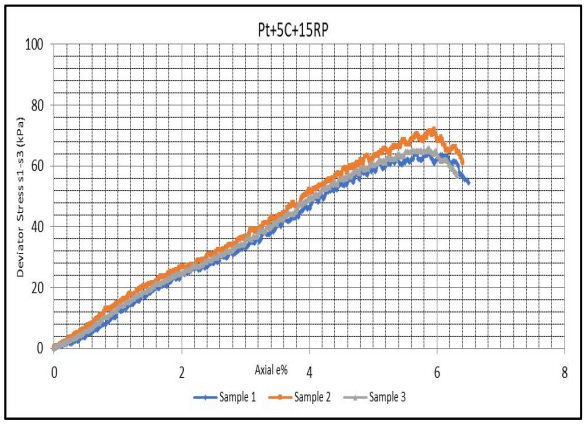

Pt+5C+15RC+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

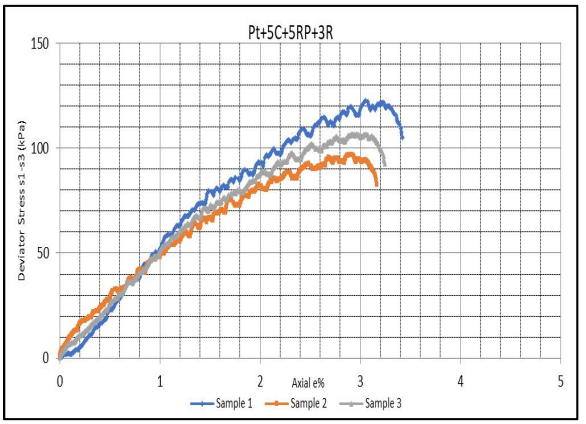

Pt+5C+15RC+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

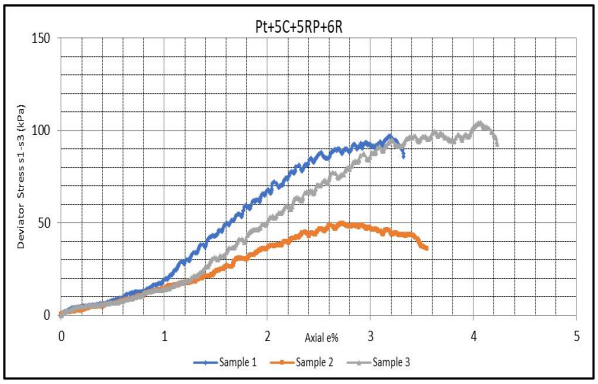

Pt+5C+15RC+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

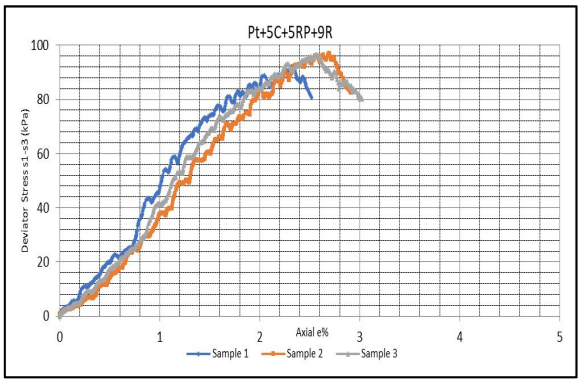

Pt+5C+5RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

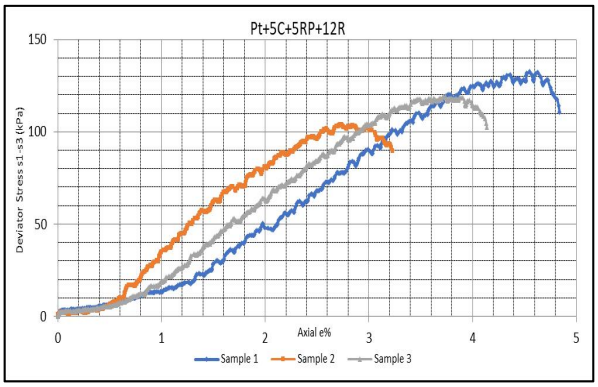

Pt+5C+10RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

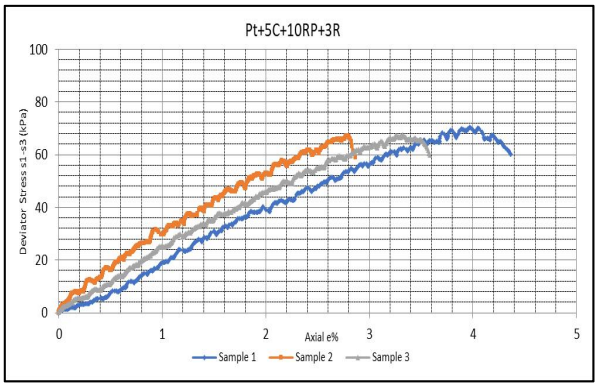

Pt+5C+15RP
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

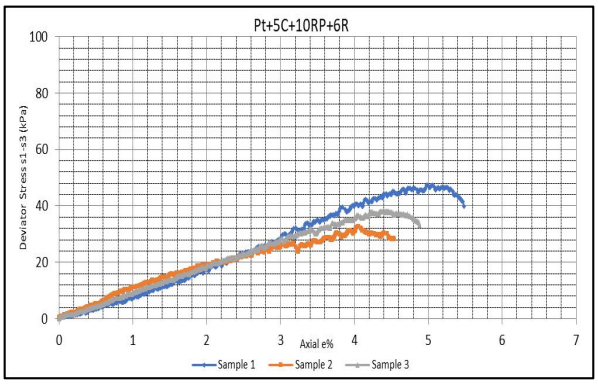

Pt+5C+5RP+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

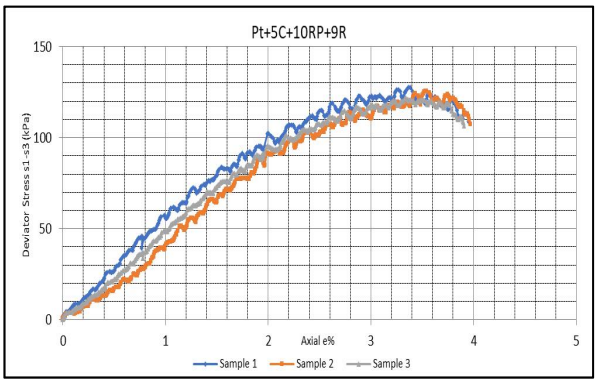

Pt+5C+5RP+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

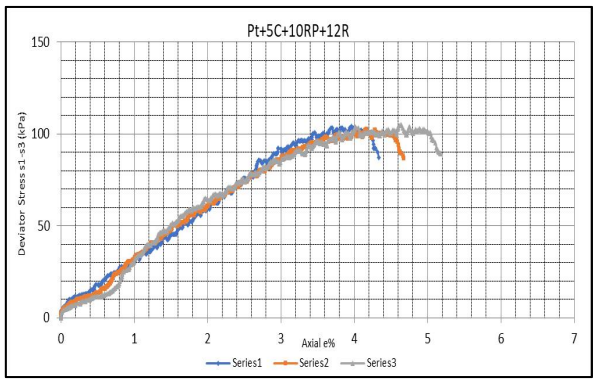

Pt+5C+5RP+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

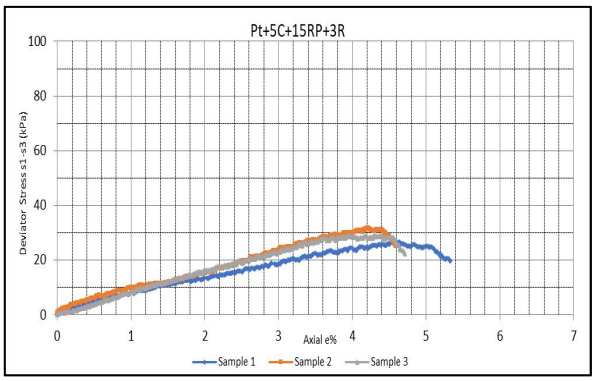

Pt+5C+5RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

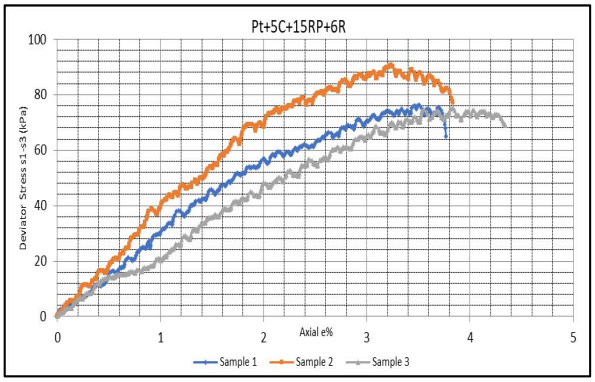

Pt+5C+10RP+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

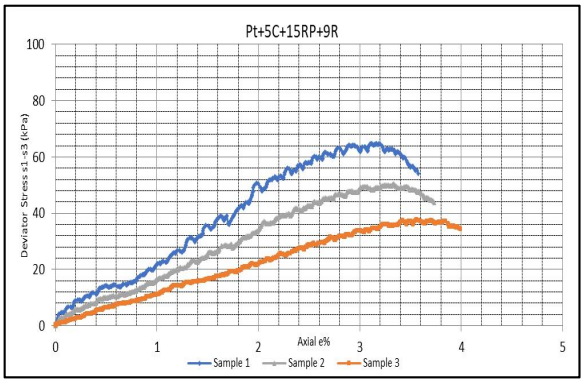

Pt+5C+10RP+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

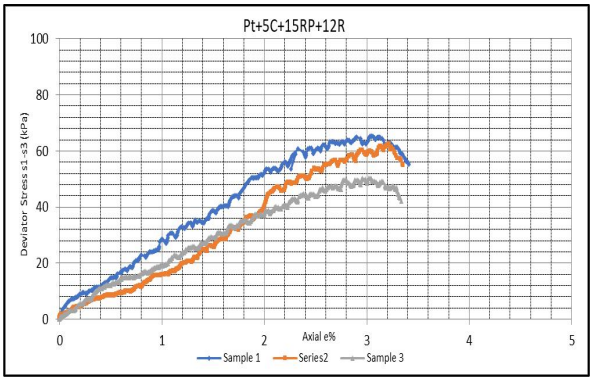

Pt+5C+10RP+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3


Pt+5C+10RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Series1
Series2
Series3


Pt+5C+15RP+3R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3


Pt+5C+15RP+6R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3

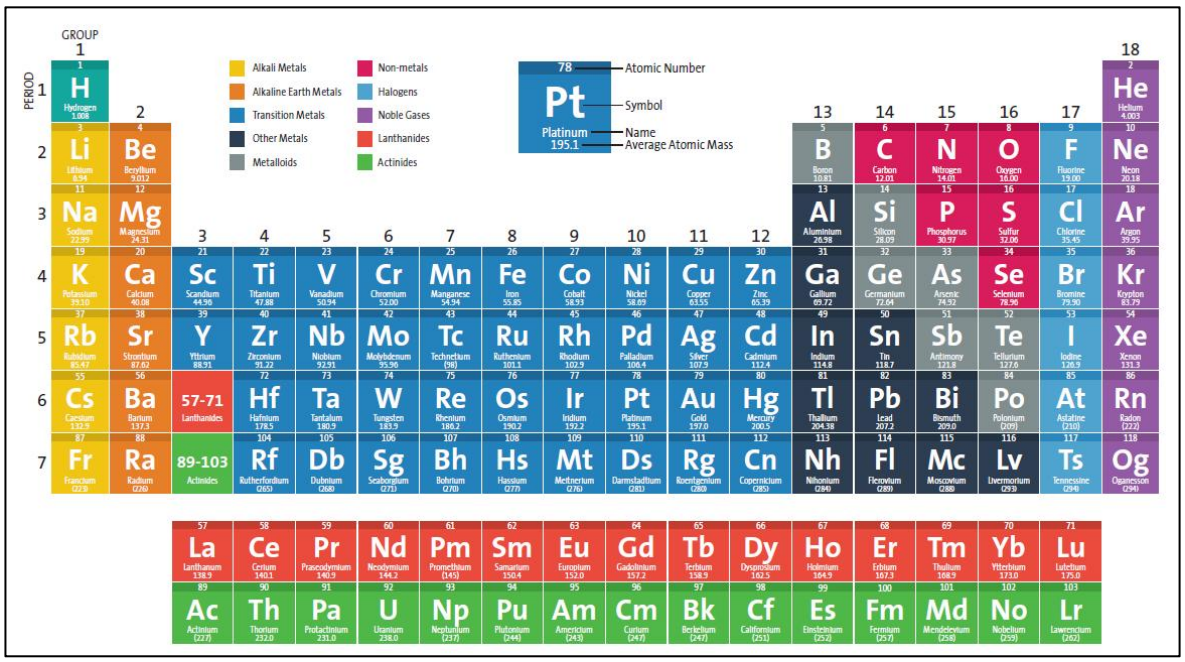

Pt+5C+15RP+9R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Sample 2
Sample 3


Pt+5C+15RP+12R
Deviator Stress s1-s3 (kPa)
Axial e%
Sample 1
Series2
Sample 3

10. Summary of CBR value

Mix Design	CBR (%)	
	7days	28days
Pt	1.2	1.7
Pt+3R	3.2	3.8
Pt+6R	24.7	14.1
Pt+12R	16.4	13.3
Pt+5C+5RC	3.9	6.2
Pt+5C+10RC	2.6	4.5
Pt+5C+15RC	1.8	2.2
Pt+5C+5RC+3R	26.2	28.3
Pt+5C+5RC+6R	24.4	28.2
Pt+5C+5RC+9R	18.5	24.9
Pt+5C+5RC+12R	11.2	8.4
Pt+5C+10RC+3R	20.6	22.5
Pt+5C+10RC+6R	24.6	25.9
Pt+5C+10RC+9R	15.7	16.1
Pt+5C+10RC+12R	10.5	10.3
Pt+5C+15RC+3R	6.1	7.4
Pt+5C+15RC+6R	12.9	20.1
Pt+5C+15RC+12R	32.0	42.0
Pt+5C+5RP	9.7	11.1
Pt+5C+5RP+3R	25.1	14.6
Pt+5C+10RP+9R	7.4	10.4
Pt+5C+10RP+12R	3.6	4.7
Pt+5C+15RP+6R	4.4	5.0

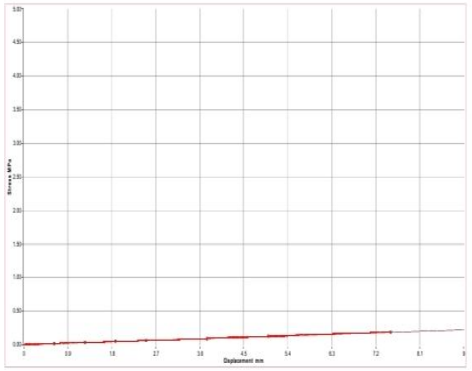
11. Periodic table of elements used in the calculation of oxide forms conversion



California bearing ratio test results (7 days)

CBR TEST REPORT
COOPER ASDDASASADASDASDASDS

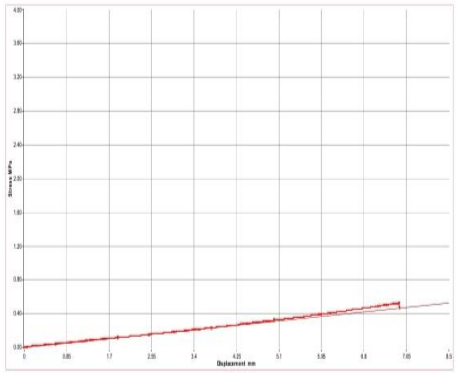
Company		Test No	
Sampled From		Test Start Date	
Material Type	Peat (7d)	Test Finish Date	



(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.040	0.02			CBR %	1.2
		1.250	0.070	0.04				
		1.875	0.100	0.05				
6.90		2.500	0.120	0.06	0.07	1.0		
88		3.750	0.180	0.09				
10.30		5.000	0.250	0.13	0.12	1.2		
13.11		7.500	0.370	0.19				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT
COOPER ASDDASASADASDASDASDS

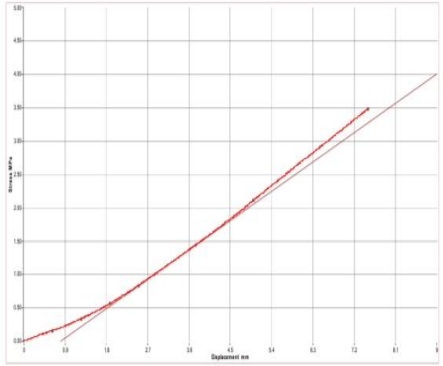
Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+3R (7d)	Test Finish Date	



(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.090	0.05			CBR %	3.2
		1.250	0.160	0.08				
		1.875	0.230	0.12				
6.90		2.500	0.300	0.16	0.16	2.3		
88		3.750	0.450	0.23				
10.30		5.000	0.630	0.33	0.33	3.2		
13.11		7.500	1.020	0.53				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT
COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+6R (7d)	Test Finish Date	

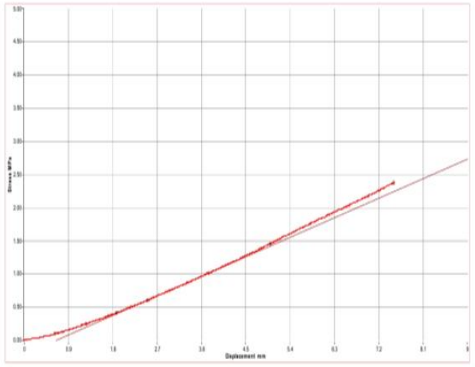


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.310	0.16			CBR %	24.7
		1.250	0.650	0.34				
		1.875	1.100	0.57				
6.90		2.500	1.610	0.83	1.22	17.9		
88		3.750	2.790	1.44				
10.30		5.000	4.080	2.11	2.55	24.7		
13.11		7.500	6.730	3.48				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+12R (7d)	Test Finish Date	



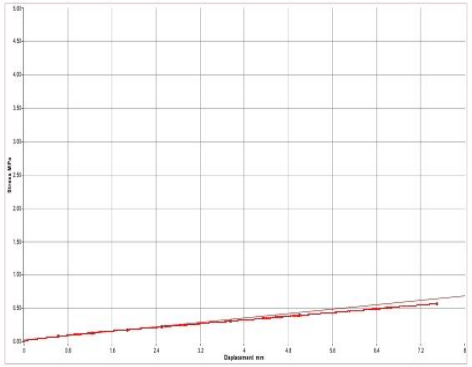
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.200	0.10			CBR %	16.4
		1.250	0.480	0.25				
		1.875	0.810	0.42				
6.90		2.500	1.170	0.61	0.81	11.9		
88		3.750	1.960	1.01				
10.30		5.000	2.820	1.46	1.70	16.4		
13.11		7.500	4.590	2.38				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC (7d)	Test Finish Date	

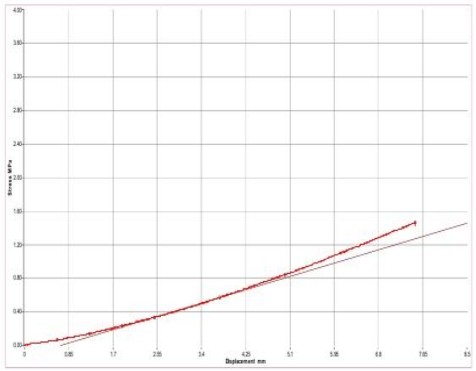


:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.160	0.08			CBR %	3.9
		1.250	0.250	0.13				
		1.875	0.350	0.18				
6.90		2.500	0.430	0.22	0.22	3.3		
88		3.750	0.600	0.31				
10.30		5.000	0.770	0.40	0.40	3.9		
13.11		7.500	1.100	0.57				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RP	Test Finish Date	



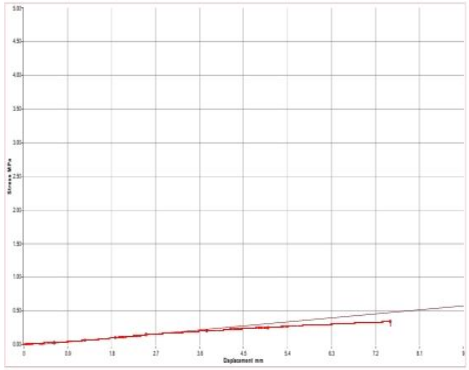
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.130	0.07			CBR %	9.7
		1.250	0.270	0.14				
		1.875	0.450	0.23				
6.90		2.500	0.650	0.34	0.46	6.7		
88		3.750	1.100	0.57				
10.30		5.000	1.630	0.84	1.00	9.7		
13.11		7.500	2.830	1.46				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC (7d)	Test Finish Date	

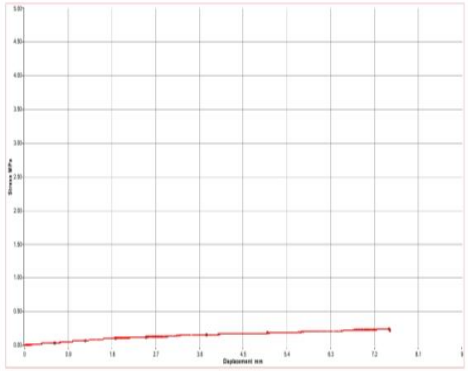


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.060	0.03			CBR %	2.6
		1.250	0.120	0.06				
		1.875	0.200	0.10				
6.90		2.500	0.280	0.14	0.16	2.3		
88		3.750	0.400	0.21				
10.30		5.000	0.490	0.25	0.27	2.6		
13.11		7.500	0.670	0.35				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC (7d)	Test Finish Date	

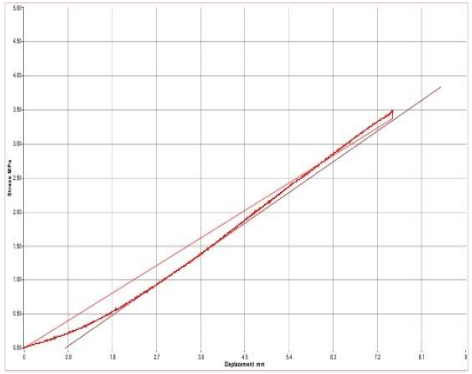


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.070	0.04			CBR %	1.8
		1.250	0.140	0.07				
		1.875	0.200	0.10				
6.90		2.500	0.240	0.12	0.12	1.8		
88		3.750	0.300	0.16				
10.30		5.000	0.360	0.19	0.19	1.8		
13.11		7.500	0.460	0.24				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RP+3R (7d)	Test Finish Date	

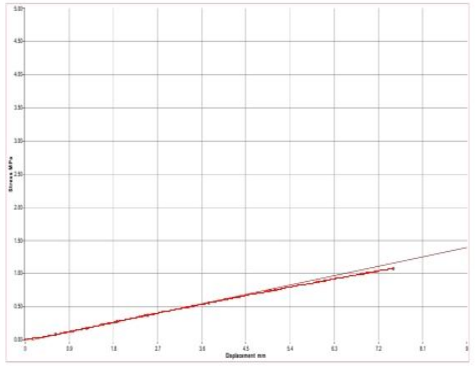


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.290	0.15			CBR %	25.1
		1.250	0.630	0.33				
		1.875	1.090	0.56				
6.90		2.500	1.610	0.83	1.25	18.3		
88		3.750	2.820	1.46				
10.30		5.000	4.150	2.15	2.60	25.1		
13.11		7.500	6.710	3.47				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RP+9R (7d)	Test Finish Date	



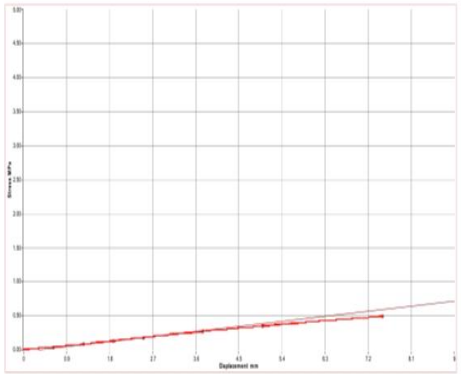
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.160	0.08			CBR %	7.4
		1.250	0.340	0.18				
		1.875	0.530	0.27				
6.90		2.500	0.720	0.37	0.39	5.8		
88		3.750	1.080	0.56				
10.30		5.000	1.430	0.74	0.76	7.4		
13.11		7.500	2.080	1.08				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RP+12R (7d)	Test Finish Date	



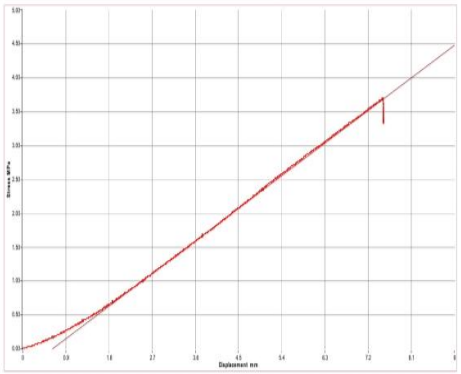
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(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.080	0.04			CBR %	3.6
		1.250	0.170	0.09				
		1.875	0.250	0.13				
6.90		2.500	0.350	0.18	0.21	3.0		
88		3.750	0.520	0.27				
10.30		5.000	0.680	0.35	0.37	3.6		
13.11		7.500	0.960	0.50				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+3R (7d)	Test Finish Date	



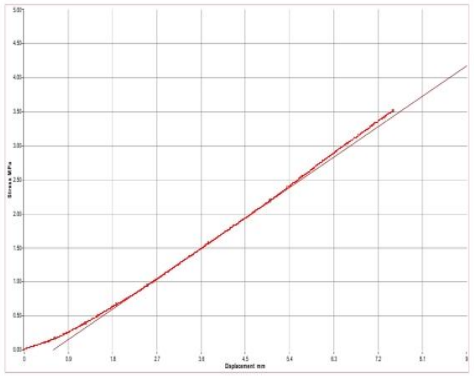
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(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.330	0.17			CBR %	26.2
		1.250	0.800	0.41				
		1.875	1.340	0.69				
6.90		2.500	1.940	1.00	1.34	19.6		
88		3.750	3.230	1.67				
10.30		5.000	4.550	2.36	2.71	26.2		
13.11		7.500	7.130	3.69				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+6R (7d)	Test Finish Date	



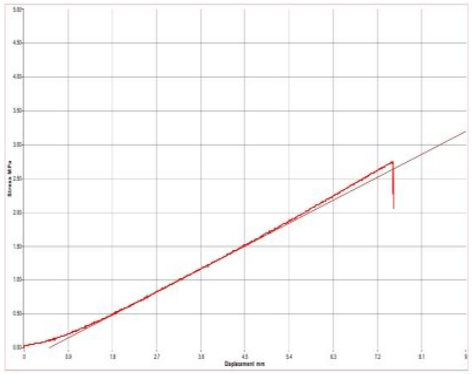
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.330	0.17			CBR %	24.4
		1.250	0.770	0.40				
		1.875	1.290	0.67				
6.90		2.500	1.830	0.95	1.24	18.2		
88		3.750	3.030	1.57				
10.30		5.000	4.240	2.19	2.52	24.4		
13.11		7.500	6.790	3.51				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+9R (7d)	Test Finish Date	



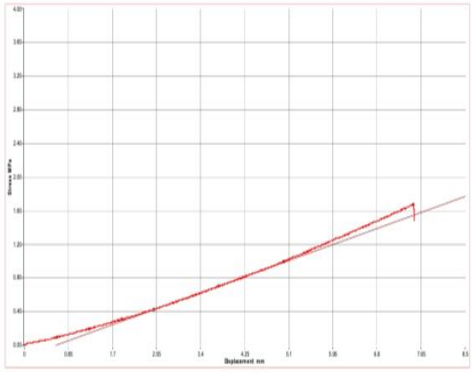
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.260	0.13			CBR %	18.5
		1.250	0.600	0.31				
		1.875	1.010	0.52				
6.90		2.500	1.450	0.75	0.94	13.8		
88		3.750	2.360	1.22				
10.30		5.000	3.310	1.71	1.91	18.5		
13.11		7.500	5.290	2.74				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+12R (7d)	Test Finish Date	



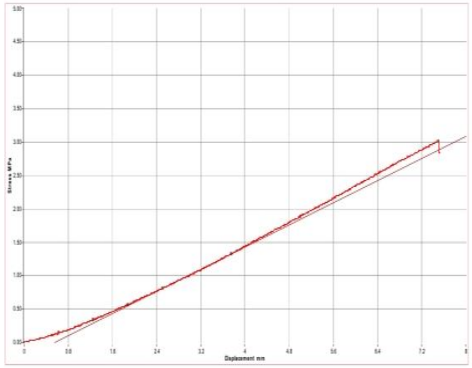
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.190	0.10			CBR %	11.2
		1.250	0.380	0.20				
		1.875	0.600	0.31				
6.90		2.500	0.820	0.42	0.55	8.1		
88		3.750	1.360	0.70				
10.30		5.000	1.920	0.99	1.16	11.2		
13.11		7.500	3.230	1.67				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+3R (7d)	Test Finish Date	



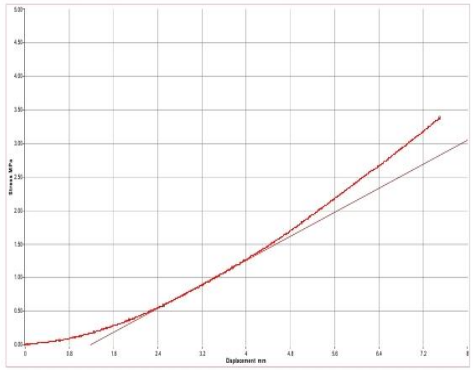
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.280	0.14			CBR %	20.6
		1.250	0.660	0.34				
		1.875	1.100	0.57				
6.90		2.500	1.560	0.81	1.03	15.1		
88		3.750	2.560	1.33				
10.30		5.000	3.650	1.89	2.13	20.6		
13.11		7.500	5.820	3.01				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+6R (7d)	Test Finish Date	



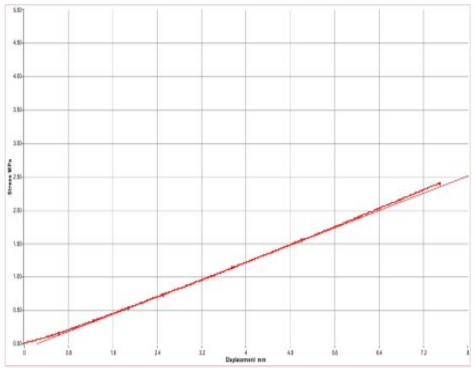
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.130	0.07			CBR %	24.6
		1.250	0.370	0.19				
		1.875	0.710	0.37				
6.90		2.500	1.140	0.59	1.12	16.4		
88		3.750	2.220	1.15				
10.30		5.000	3.520	1.82	2.55	24.6		
13.11		7.500	6.530	3.38				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+9R (7d)	Test Finish Date	



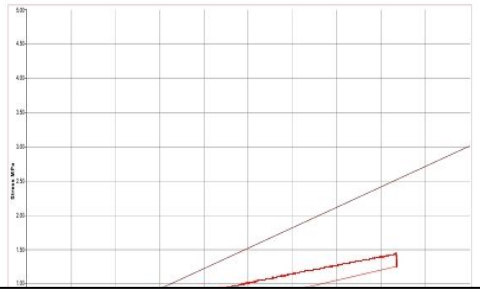
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.310	0.16			CBR %	15.7
		1.250	0.670	0.35				
		1.875	1.050	0.54				
6.90		2.500	1.420	0.73	0.81	11.8		
88		3.750	2.200	1.14				
10.30		5.000	3.000	1.55	1.63	15.7		
13.11		7.500	4.640	2.40				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

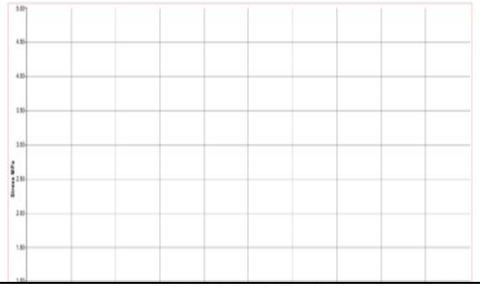
Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+12R (7d)	Test Finish Date	



CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

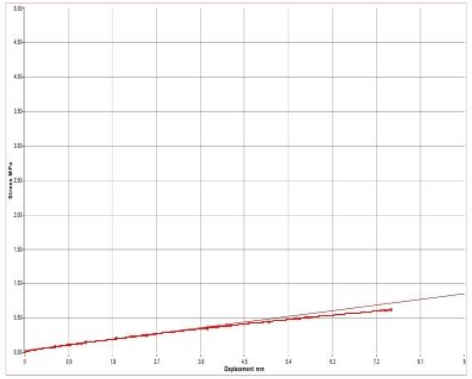
Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+3R (7d)	Test Finish Date	



CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RP+6R (7d)	Test Finish Date	



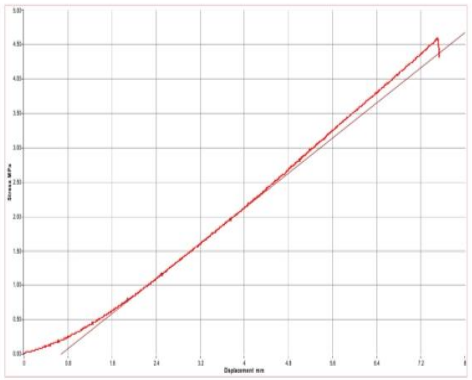
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR	
		0.625	0.170	0.09		CBR %	4.4
		1.250	0.280	0.14			
		1.875	0.390	0.20			
6.90		2.500	0.490	0.25	0.25	3.7	
88		3.750	0.690	0.36			
10.30		5.000	0.870	0.45	0.45	4.4	
13.11		7.500	1.210	0.63			
15.87		10.000	0.000	0.00			
17.94		12.500	0.000	0.00			

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+12R (7d)	Test Finish Date	



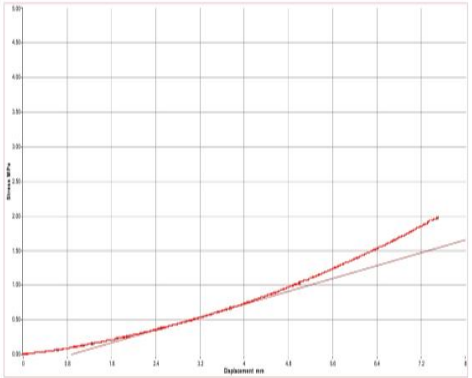
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.360	0.19			CBR %	32.0
		1.250	0.880	0.46				
		1.875	1.520	0.79				
6.90		2.500	2.250	1.16	1.59	23.3		
88		3.750	3.790	1.96				
10.30		5.000	5.450	2.82	3.31	32.0		
13.11		7.500	8.850	4.58				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+6R (7d)	Test Finish Date	



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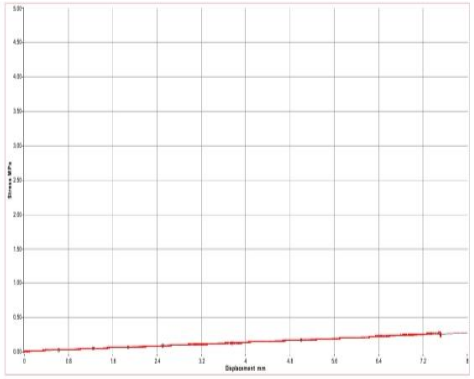
(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.130	0.07			CBR %	12.9
		1.250	0.310	0.16				
		1.875	0.500	0.26				
6.90		2.500	0.730	0.38	0.57	8.4		
88		3.750	1.290	0.67				
10.30		5.000	2.000	1.04	1.34	12.9		
13.11		7.500	3.830	1.98				
15.87		10.000						
17.94		12.500						

California bearing ratio test results (28 days)

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Peat (28d)	Test Finish Date	

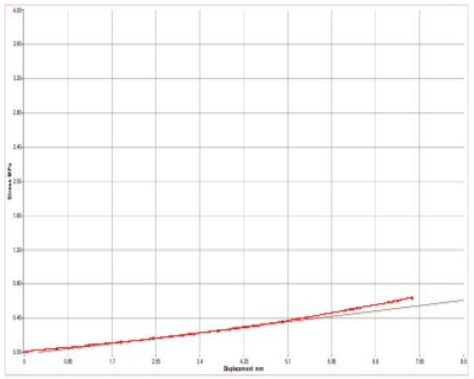


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.060	0.03			CBR %	1.7
		1.250	0.100	0.05				
		1.875	0.140	0.07				
6.90		2.500	0.180	0.09	0.09	1.4		
88		3.750	0.250	0.13				
10.30		5.000	0.340	0.18	0.18	1.7		
13.11		7.500	0.540	0.28				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+3R (28d)	Test Finish Date	

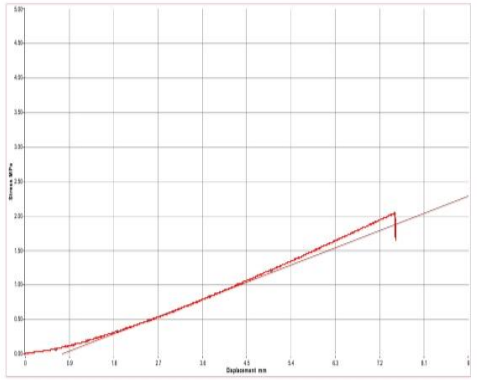


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.090	0.05			CBR %	3.8
		1.250	0.160	0.08				
		1.875	0.230	0.12				
6.90		2.500	0.320	0.17	0.18	2.7		
88		3.750	0.490	0.25				
10.30		5.000	0.700	0.36	0.39	3.8		
13.11		7.500	1.240	0.64				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+6R (28d)	Test Finish Date	

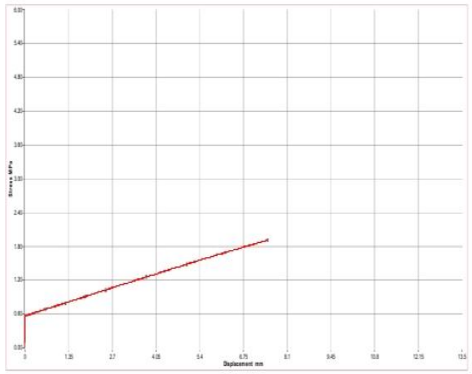


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.150	0.08			CBR %	14.1
		1.250	0.370	0.19				
		1.875	0.630	0.33				
6.90		2.500	0.940	0.49	0.69	10.1		
88		3.750	1.610	0.83				
10.30		5.000	2.350	1.22	1.46	14.1		
13.11		7.500	3.930	2.03				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

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Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+12R (28d)	Test Finish Date	



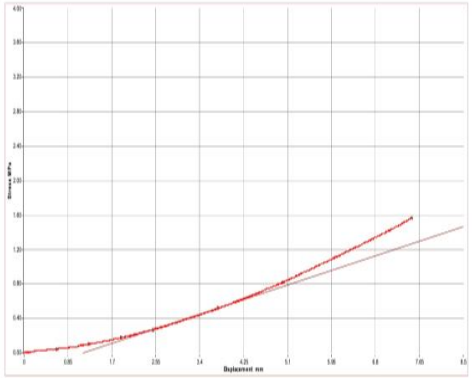
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(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	1.330	0.69			CBR %	14.4
		1.250	1.540	0.80				
		1.875	1.760	0.91				
6.90		2.500	1.990	1.03	1.03	15.1		
88		3.750	2.440	1.26				
10.30		5.000	2.870	1.49	1.49	14.4		
13.11		7.500	3.700	1.92				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RP (28d)	Test Finish Date	



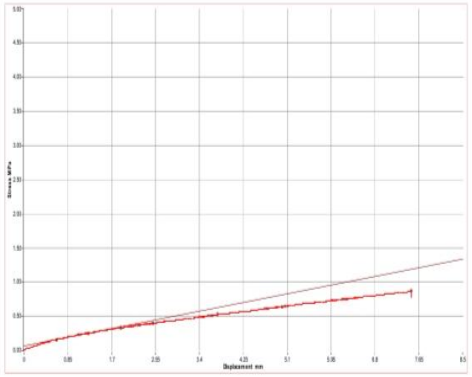
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.090	0.05			CBR %	11.1
		1.250	0.200	0.10				
		1.875	0.340	0.18				
6.90		2.500	0.520	0.27	0.49	7.2		
88		3.750	1.000	0.52				
10.30		5.000	1.580	0.82	1.15	11.1		
13.11		7.500	3.020	1.56				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC (28d)	Test Finish Date	



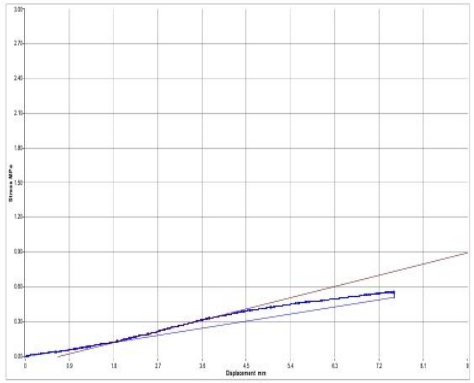
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.310	0.16			CBR %	6.2
		1.250	0.490	0.25				
		1.875	0.650	0.34				
6.90		2.500	0.770	0.40	0.40	5.8		
88		3.750	1.020	0.53				
10.30		5.000	1.240	0.64	0.64	6.2		
13.11		7.500	1.680	0.87				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC (28d)	Test Finish Date	



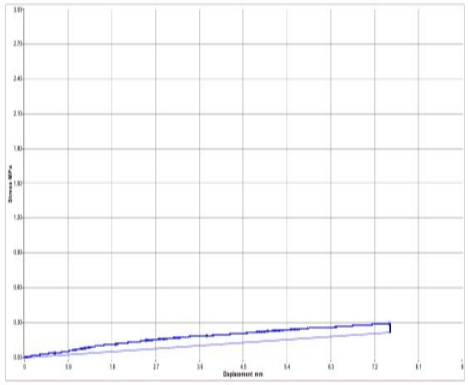
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.080	0.04			CBR %	4.5
		1.250	0.160	0.08				
		1.875	0.260	0.13				
6.90		2.500	0.380	0.20	0.27	3.9		
		3.750	0.640	0.33				
10.30		5.000	0.830	0.43	0.47	4.5		
		7.500	1.080	0.56				
		10.000						
		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC (28d)	Test Finish Date	



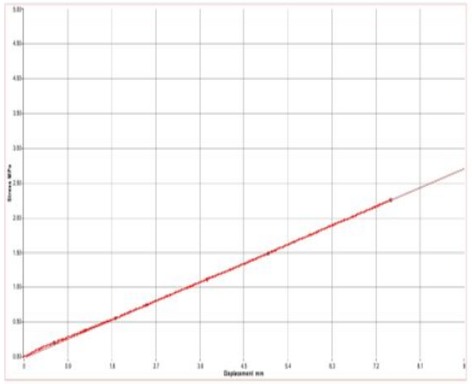
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.080	0.04			CBR %	2.2
		1.250	0.160	0.08				
		1.875	0.230	0.12				
6.90		2.500	0.290	0.15	0.15	2.2		
		3.750	0.370	0.19				
10.30		5.000	0.440	0.23	0.23	2.2		
		7.500	0.570	0.30				
		10.000						
		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RP+3R (28d)	Test Finish Date	



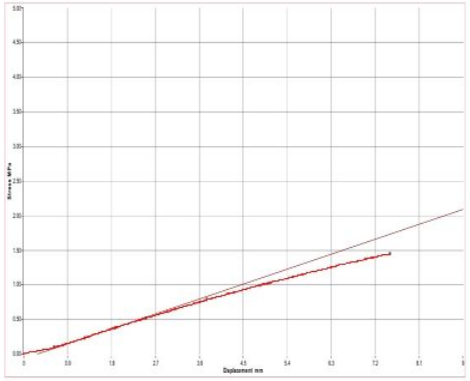
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.400	0.21			CBR %	14.6
		1.250	0.740	0.38				
		1.875	1.080	0.56				
6.90		2.500	1.430	0.74	0.76	11.1		
88		3.750	2.160	1.12				
10.30		5.000	2.880	1.49	1.51	14.6		
13.11		7.500	4.360	2.26				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RP+9R (28d)	Test Finish Date	

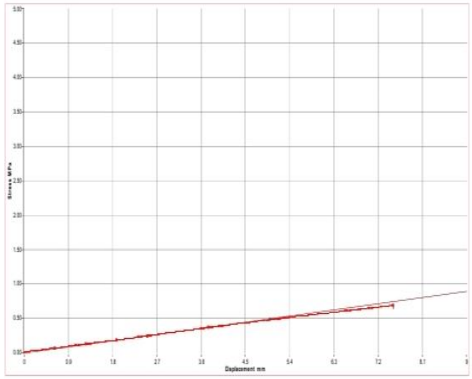


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.190	0.10			CBR %	10.4
		1.250	0.450	0.23				
		1.875	0.740	0.38				
6.90		2.500	1.010	0.52	0.58	8.5		
88		3.750	1.520	0.79				
10.30		5.000	1.980	1.02	1.08	10.4		
13.11		7.500	2.800	1.45				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RP+12R (28d)	Test Finish Date	

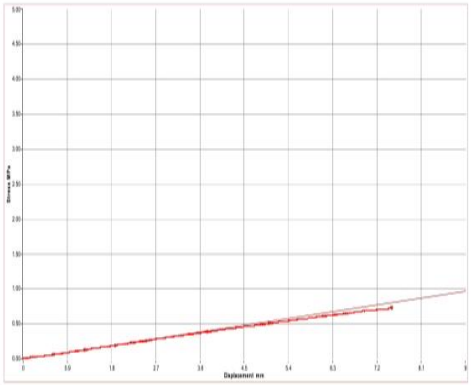


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.140	0.07			CBR %	4.7
		1.250	0.250	0.13				
		1.875	0.360	0.19				
6.90		2.500	0.470	0.24	0.25	3.6		
88		3.750	0.710	0.37				
10.30		5.000	0.930	0.48	0.49	4.7		
13.11		7.500	1.320	0.68				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RP+6R (28d)	Test Finish Date	

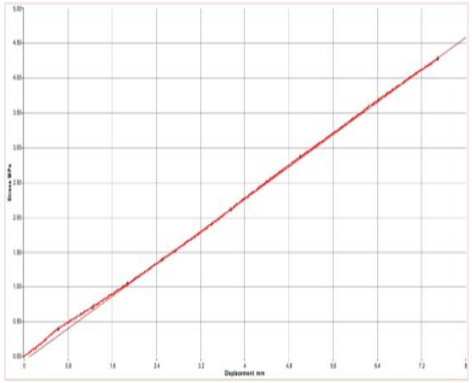


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.120	0.06			CBR %	5.0
		1.250	0.250	0.13				
		1.875	0.380	0.20				
6.90		2.500	0.500	0.26	0.26	3.9		
88		3.750	0.750	0.39				
10.30		5.000	0.980	0.51	0.51	5.0		
13.11		7.500	1.410	0.73				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+3R (28d)	Test Finish Date	



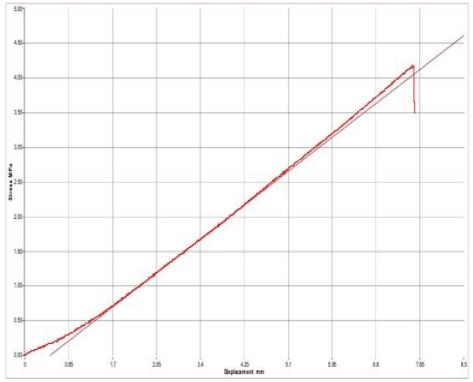
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.780	0.40			CBR %	28.3
		1.250	1.390	0.72				
		1.875	2.030	1.05				
6.90		2.500	2.690	1.39	1.44	21.1		
88		3.750	4.090	2.12				
10.30		5.000	5.540	2.87	2.92	28.3		
13.11		7.500	8.270	4.28				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+6R (28d)	Test Finish Date	



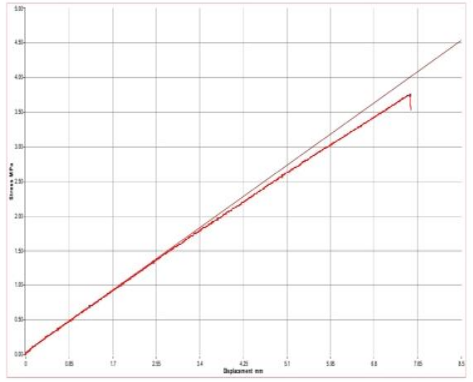
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.420	0.22			CBR %	28.2
		1.250	0.940	0.49				
		1.875	1.570	0.81				
6.90		2.500	2.240	1.16	1.44	21.1		
88		3.750	3.630	1.88				
10.30		5.000	5.090	2.63	2.92	28.2		
13.11		7.500	8.040	4.16				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+9R (28d)	Test Finish Date	



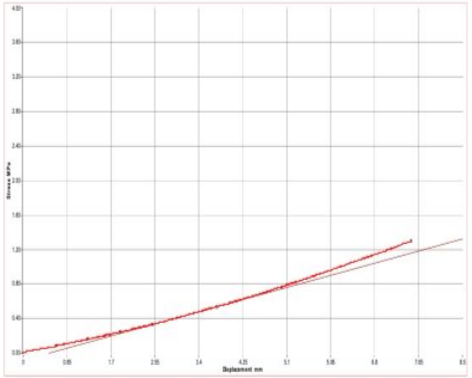
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.700	0.36			CBR %	24.9
		1.250	1.340	0.69				
		1.875	1.960	1.01				
6.90		2.500	2.590	1.34	1.34	19.6		
88		3.750	3.780	1.96				
10.30		5.000	4.970	2.57	2.57	24.9		
13.11		7.500	7.240	3.75				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+5RC+12R (28d)	Test Finish Date	

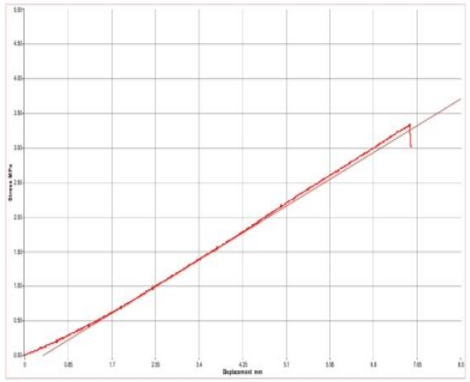


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.160	0.08			CBR %	8.4
		1.250	0.310	0.16				
		1.875	0.470	0.24				
6.90		2.500	0.640	0.33	0.41	6.1		
88		3.750	1.040	0.54				
10.30		5.000	1.480	0.77	0.87	8.4		
13.11		7.500	2.510	1.30				
15.87		10.000	0.000	0.00				
17.94		12.500	0.000	0.00				

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+3R (28d)	Test Finish Date	

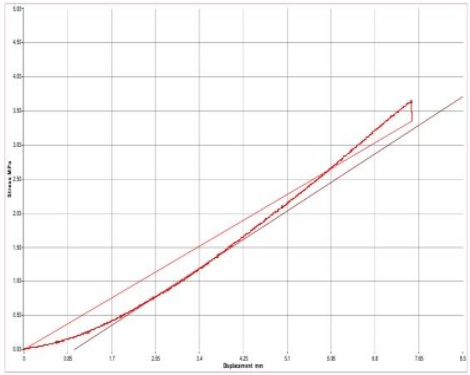


(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.400	0.21			CBR %	22.5
		1.250	0.850	0.44				
		1.875	1.350	0.70				
6.90		2.500	1.890	0.98	1.14	16.7		
88		3.750	2.990	1.55				
10.30		5.000	4.180	2.16	2.33	22.5		
13.11		7.500	6.430	3.33				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+6R (28d)	Test Finish Date	



(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.200	0.10			CBR %	25.9
		1.250	0.510	0.26				
		1.875	0.940	0.49				
6.90		2.500	1.450	0.75	1.22	17.9		
88		3.750	2.640	1.37				
10.30		5.000	4.040	2.09	2.68	25.9		
13.11		7.500	7.020	3.63				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

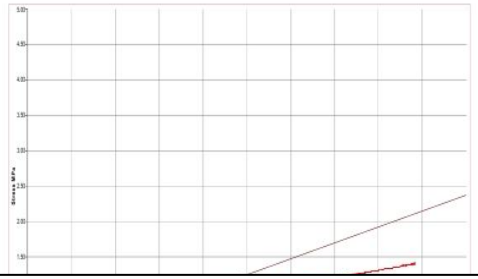
Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+9R (28d)	Test Finish Date	



CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

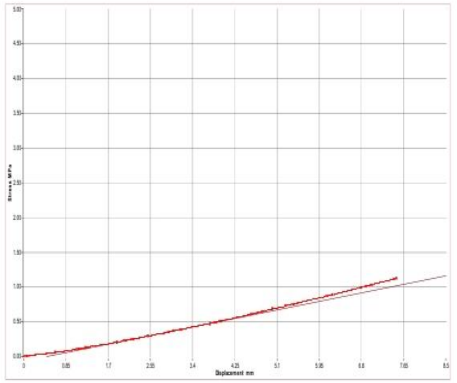
Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+10RC+12R (28d)	Test Finish Date	



CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+3R (28d)	Test Finish Date	



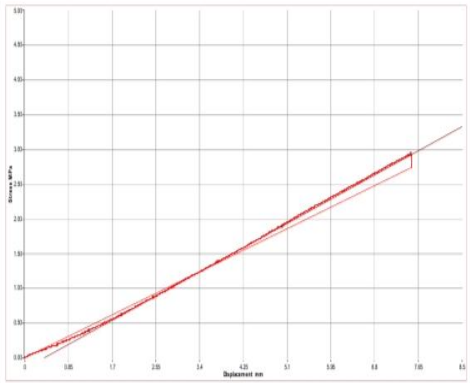
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.120	0.06			CBR %	7.4
		1.250	0.250	0.13				
		1.875	0.400	0.21				
6.90		2.500	0.570	0.30	0.36	5.3		
88		3.750	0.920	0.48				
10.30		5.000	1.320	0.68	0.76	7.4		
13.11		7.500	2.170	1.12				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+6R (28d)	Test Finish Date	



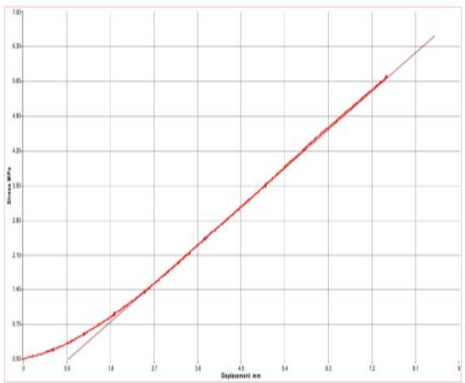
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.380	0.20			CBR %	20.1
		1.250	0.770	0.40				
		1.875	1.200	0.62				
6.90		2.500	1.680	0.87	1.02	15.0		
88		3.750	2.670	1.38				
10.30		5.000	3.670	1.90	2.08	20.1		
13.11		7.500	5.670	2.93				
15.87		10.000						
17.94		12.500						

CBR TEST REPORT

COOPER ASDDASASADASDASDASDS

Company		Test No	
Sampled From		Test Start Date	
Material Type	Pt+5C+15RC+12R (28d)	Test Finish Date	



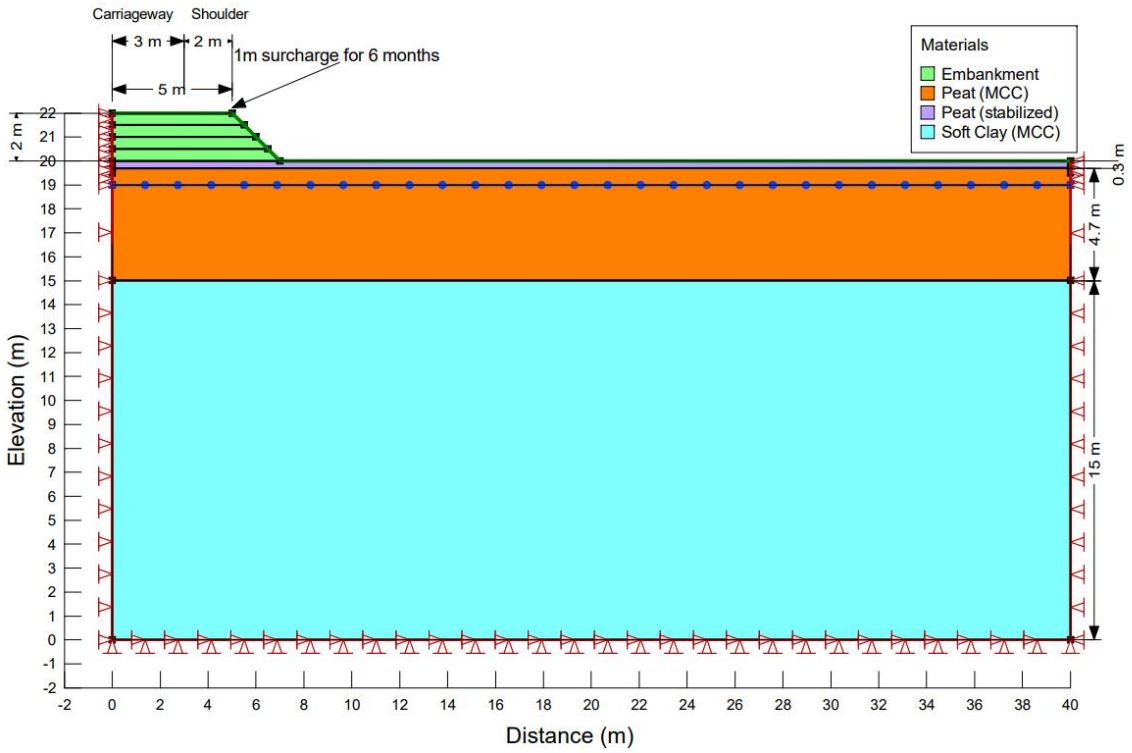
:

(MPa)		(mm)	(kN)	(MPa)	(MPa)	%CBR		
		0.625	0.380	0.20			CBR %	42.0
		1.250	0.970	0.50				
		1.875	1.750	0.91				
6.90		2.500	2.620	1.36	2.13	31.2		
88		3.750	4.700	2.43				
10.30		5.000	6.760	3.50	4.35	42.0		
13.11		7.500	11.000	5.69				
15.87		10.000						
17.94		12.500						

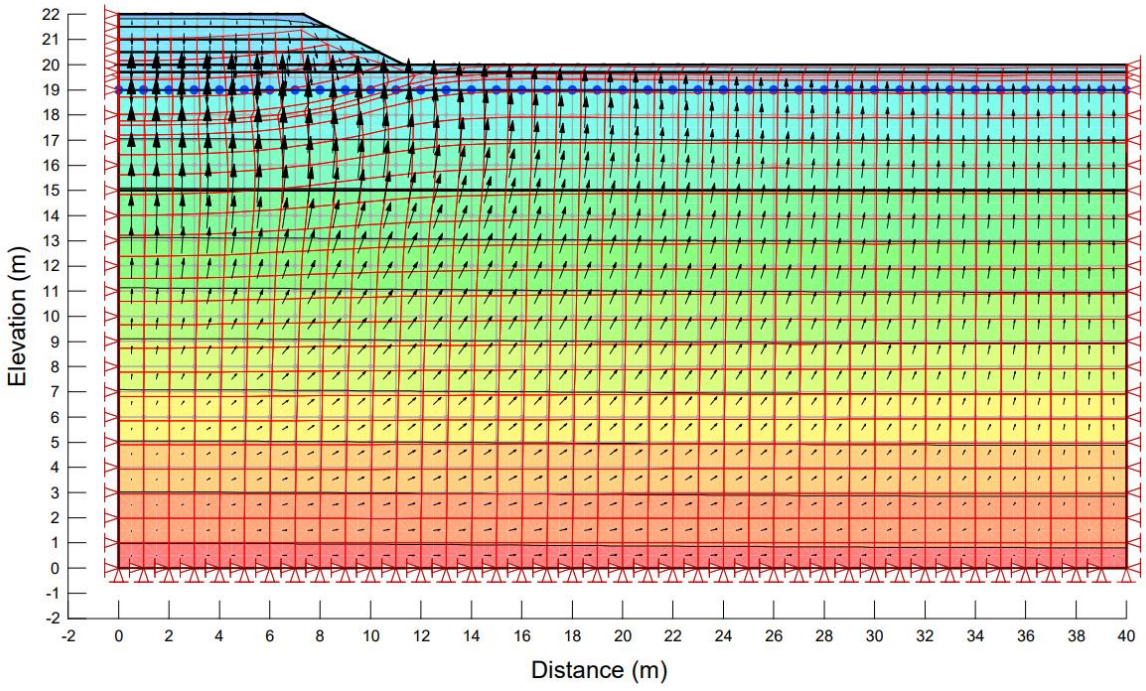
Appendix B: Modelling by GeoStudio

1. 0.3m stabilization

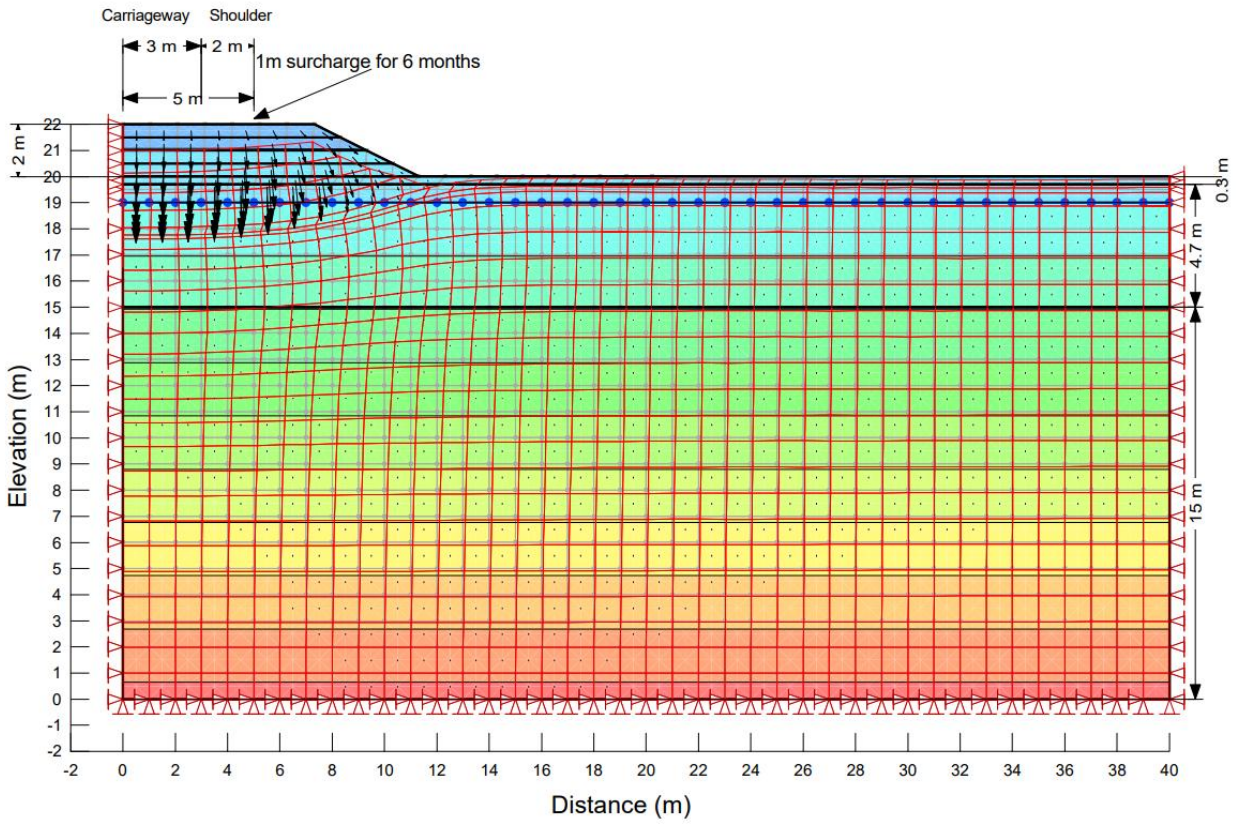
(i) Modelled Geometry and FoS for 0.3m peat stabilization



(ii) 6 months surcharge period

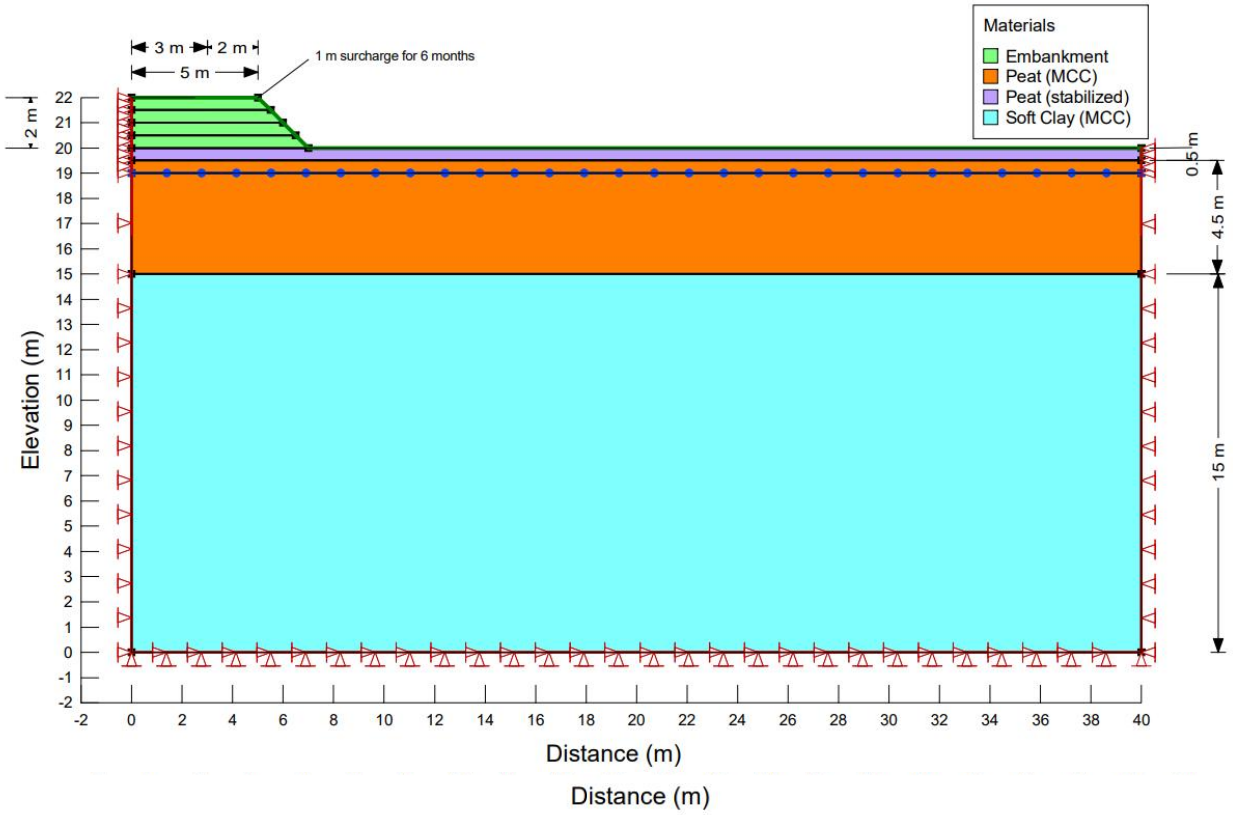


(ii) 3 years after construction

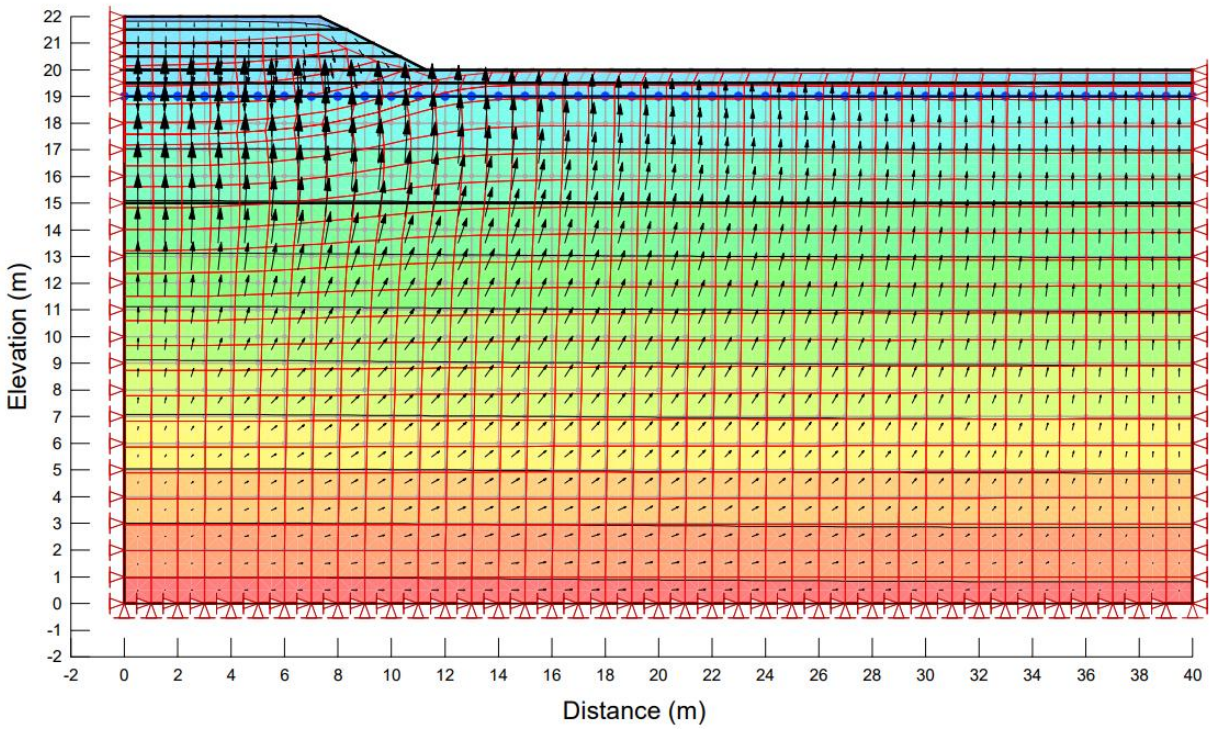


2. 0.5m stabilization

(i) Modelled Geometry and FoS for 0.5m peat stabilization



(i) 6 months surcharge period


Elevation (m)
Distance (m)
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-2
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40

(ii) 3 years after construction

